Calibration of a Magnet used for Hall Probes Calibration in Mu2e Experiment

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Introduction

- Mu2e is an experiment with the goal of determining conversion properties of muons to electrons
- The magnetic field of the Detector Solenoid must be mapped with a precision of better then 10^{-4} T
- Hall Probes will be used to map the field (3D) and Nuclear Magnetic Resonance (NMR) Probes to determine the absolute field value

Hall Probes need to be calibrated in the intended measurement range at a known homogeneous magnetic field much better than 10^{-4} T

Introduction

Calibration Magnet

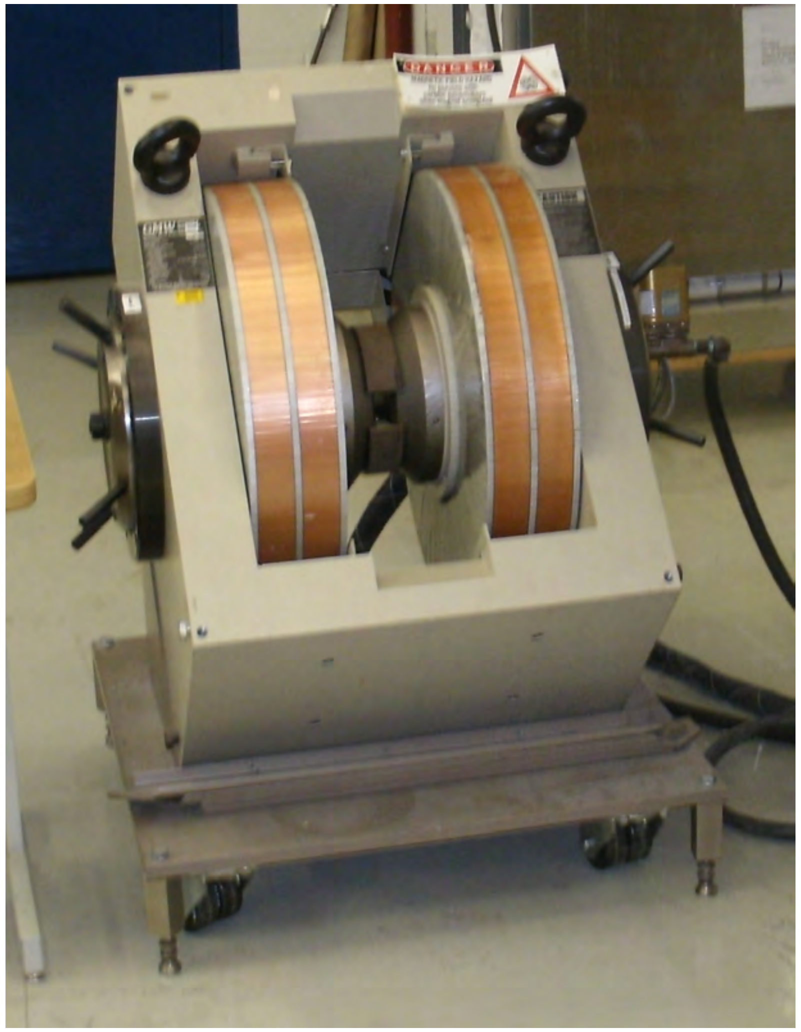


Fig.1. GMW 3474-140/280 250 mm Electromagnet.

Field **homogeneity** much better than $\mathbf{10^{-4}}$ **T** in a region of 2 cm x 2 cm

Field **stability** over time

needed for the Hall Probes calibration

Main goal: Meet the magnetic field requirements

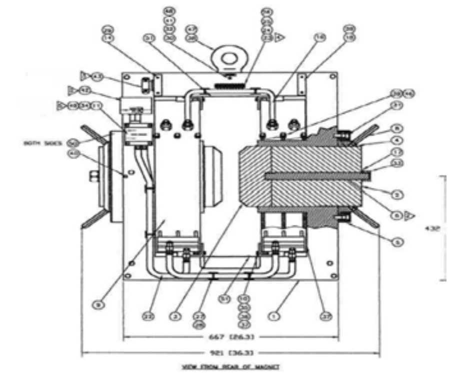
Hard constraint: a lot of factors decrease the field homogeneity and stability, compared to the ideal case.

Pole skewness
Hysteresis
Field saturation

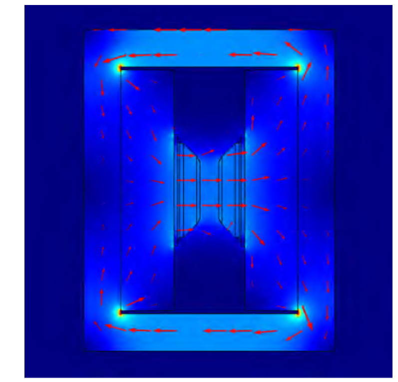
Fermilab

Introduction

How to reach the goal:



✓ Study the magnet design using the manual



✓ COMSOL simulations of the magnetic field generated by the magnet

✓ Field mapping using NMR Probes mounted on a 2 axis motion robot with LabVIEW interface.

➢ Shimming procedure to achieve a homogeneous field

- Shims are thin metal strips that adjust the field
- Iterative procedure

Fermilab

Magnet Design

Coils:
360 turns for each coil
Coils are connected in parallel

Handle
to adjust the pole gap in a range of 0 – 160 mm

Yoke

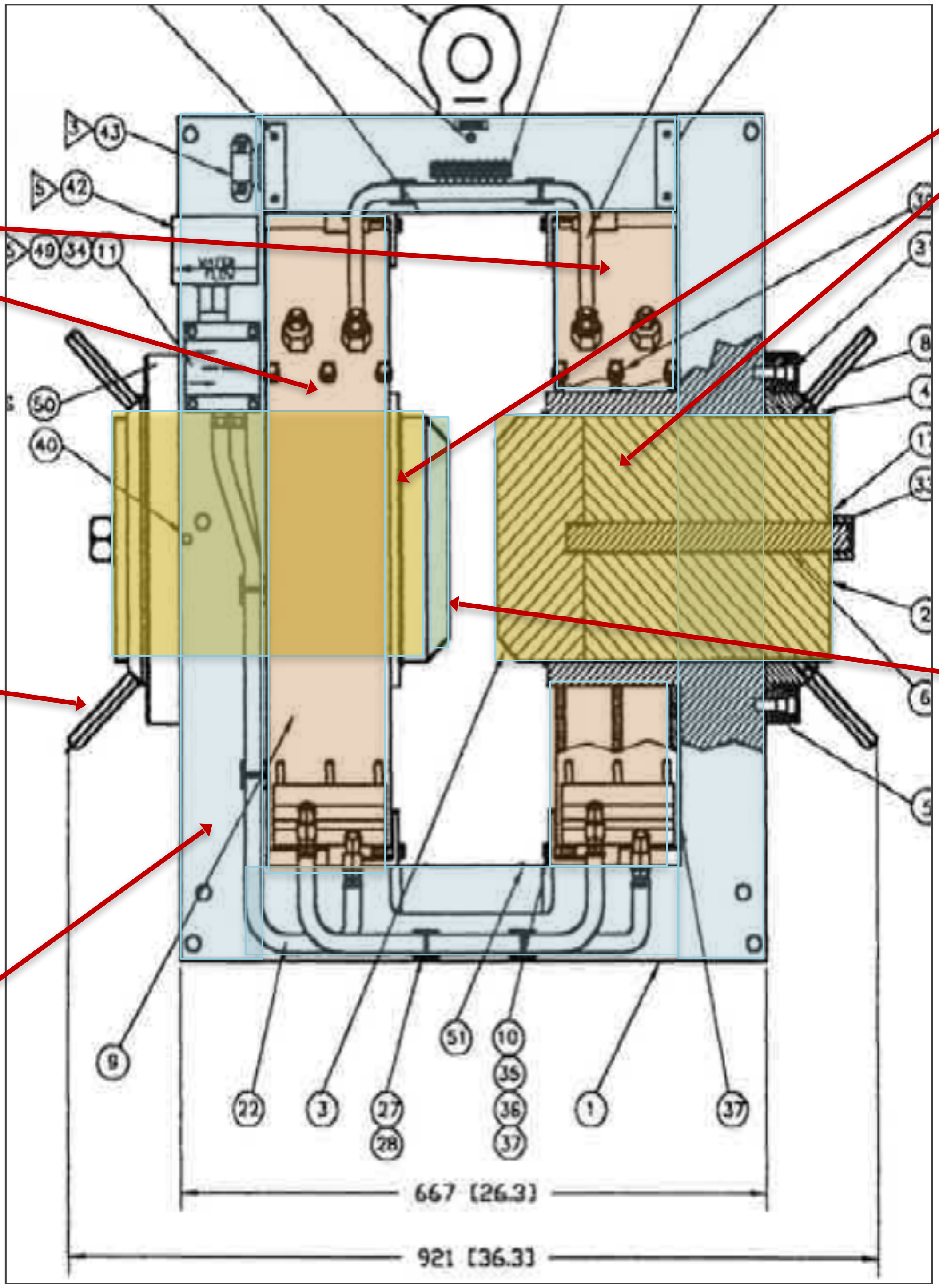


Fig.2. View from rear of magnet.

Poles
250 mm diameter

Pole cap
used to increase the magnetic field and the homogeneity

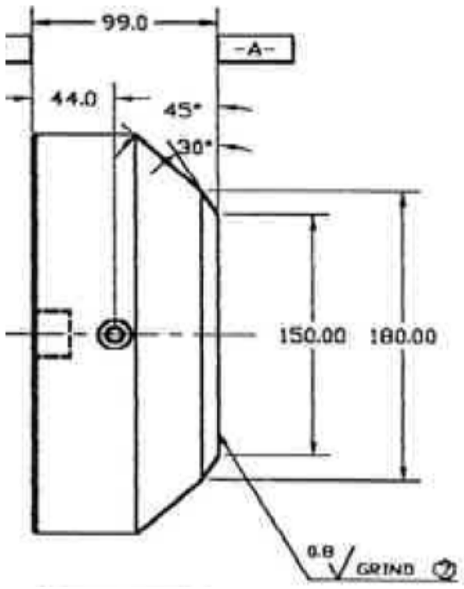
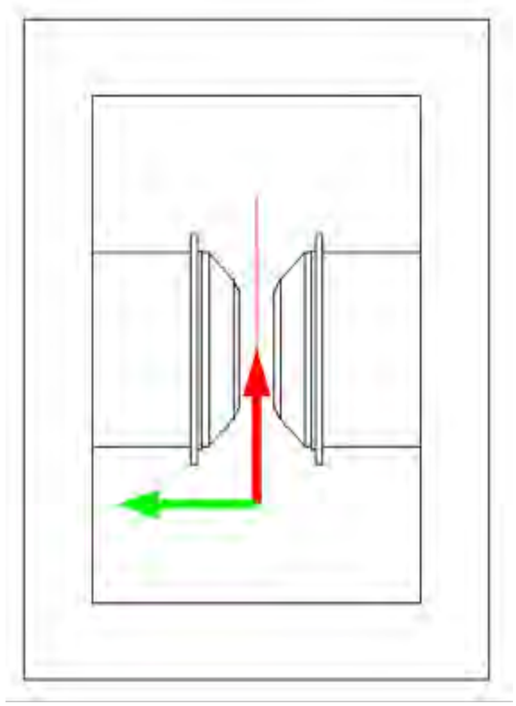


Fig.3. Pole Cap.

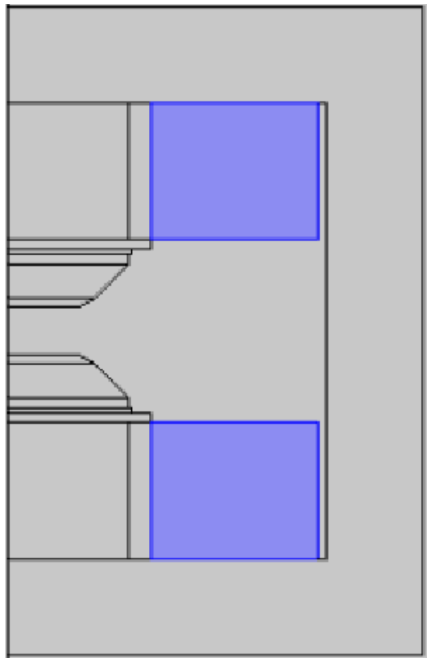
COMSOL Simulations (Finite Element Method) - Models

Models of the magnet

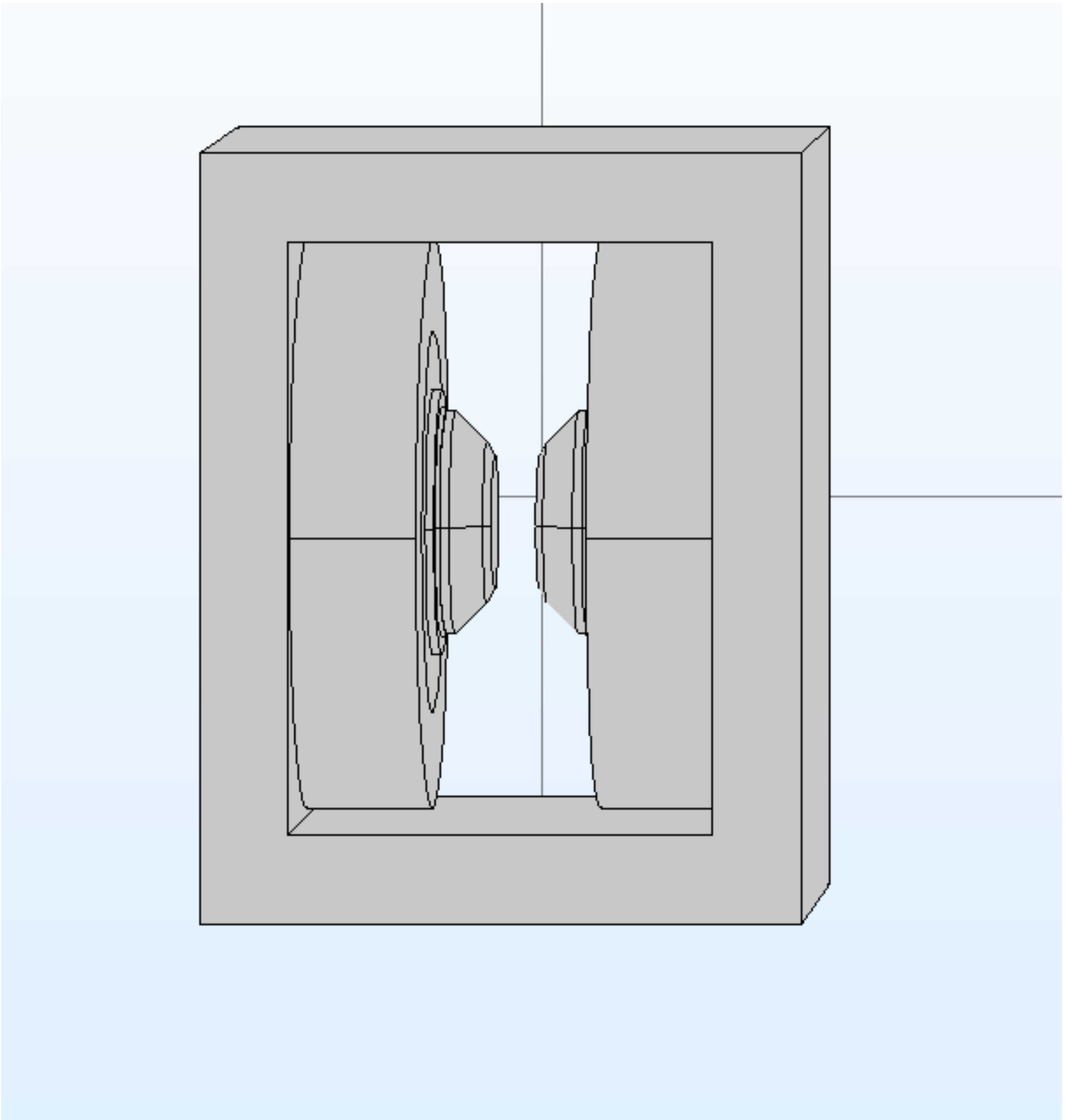
- 2D



- 2D Axisymmetric



- more realistic **3D Model**



- shape, dimensions and materials are taken from the manual

COMSOL Simulations - Ideal Case

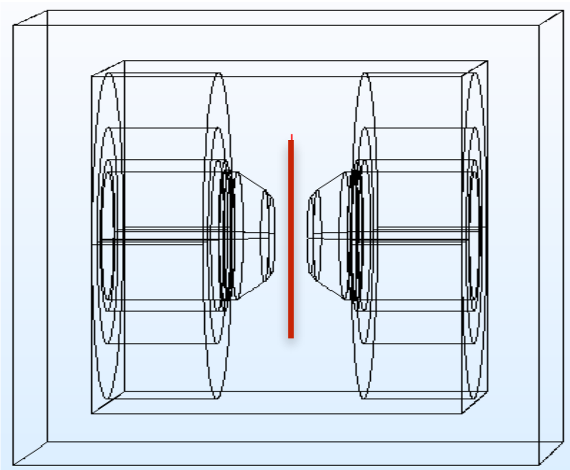
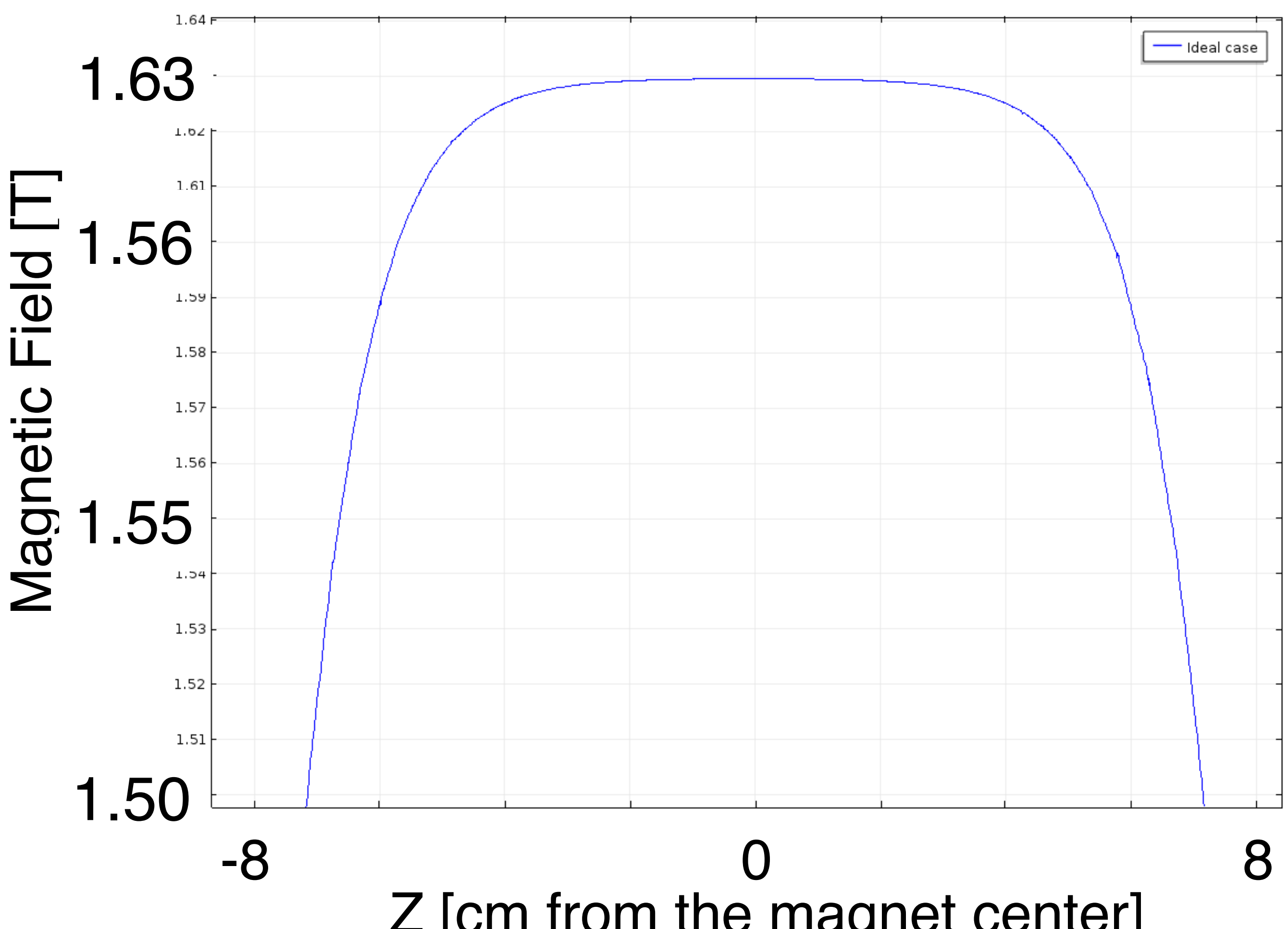


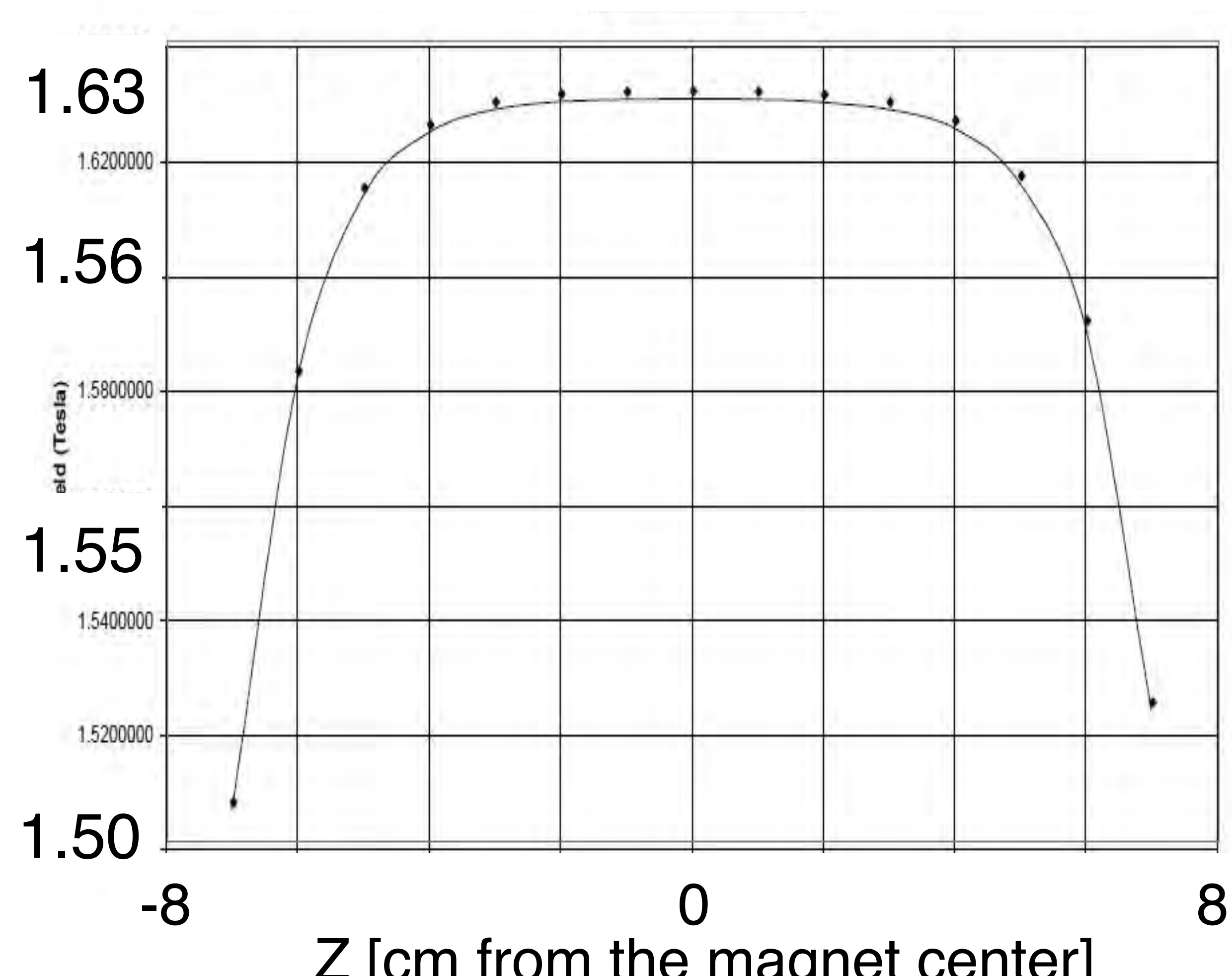
Fig.4. Z line.

Magnetic field along z direction line in the magnet center

COMSOL Simulation

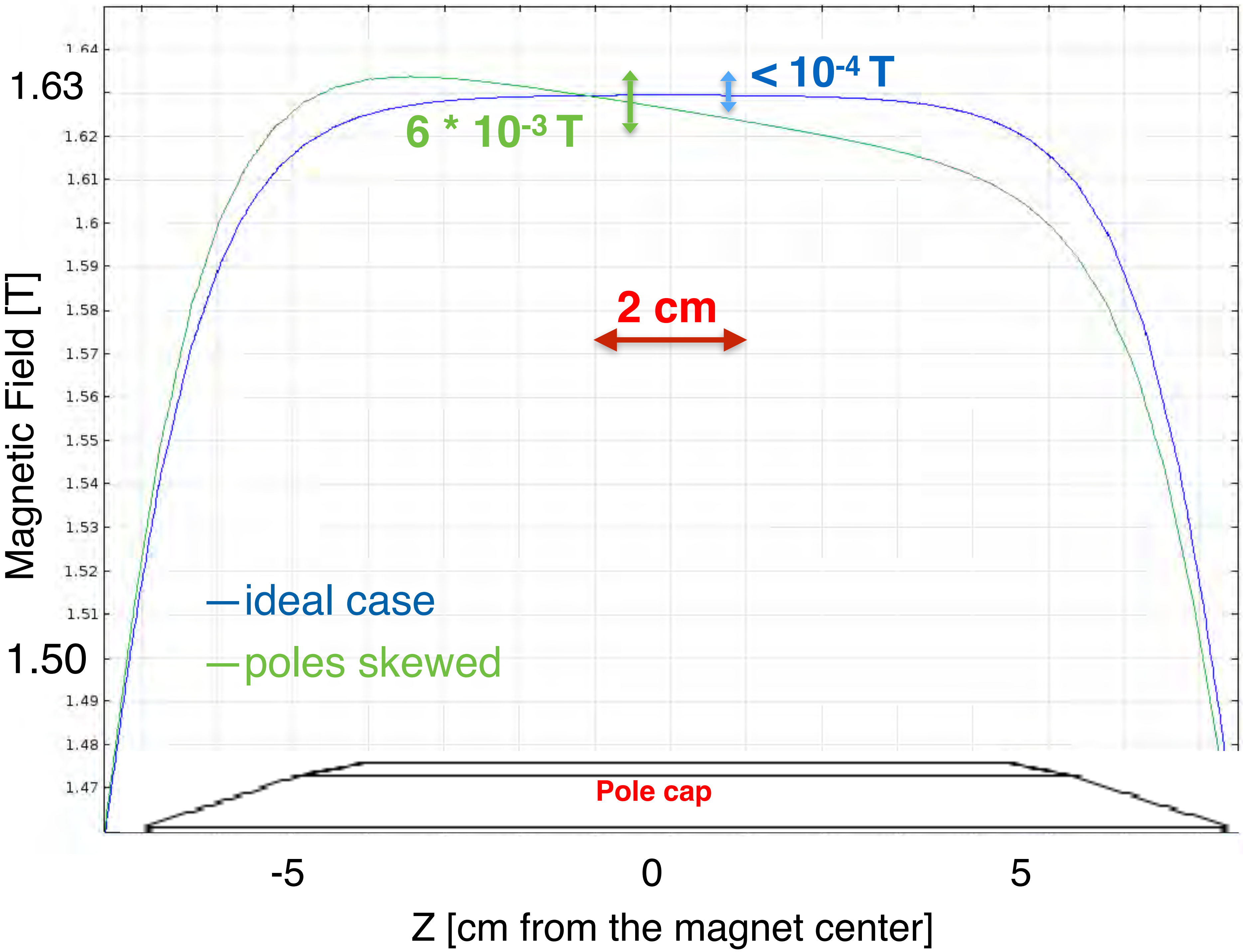


Datasheet of the magnet



COMSOL Simulations – Ideal case Vs poles skewed

Field along Z line in the magnet center. Ideal case Vs poles skewed



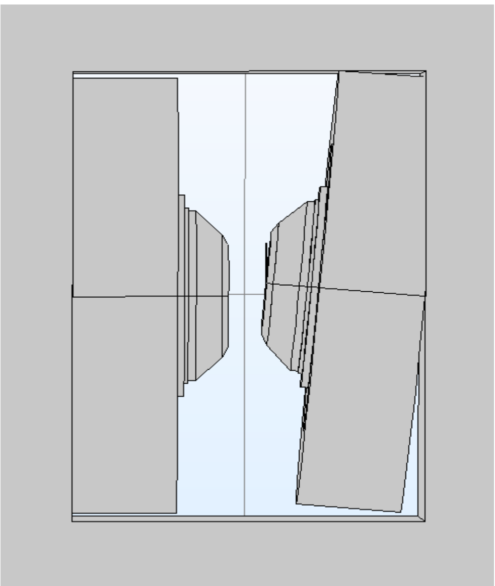
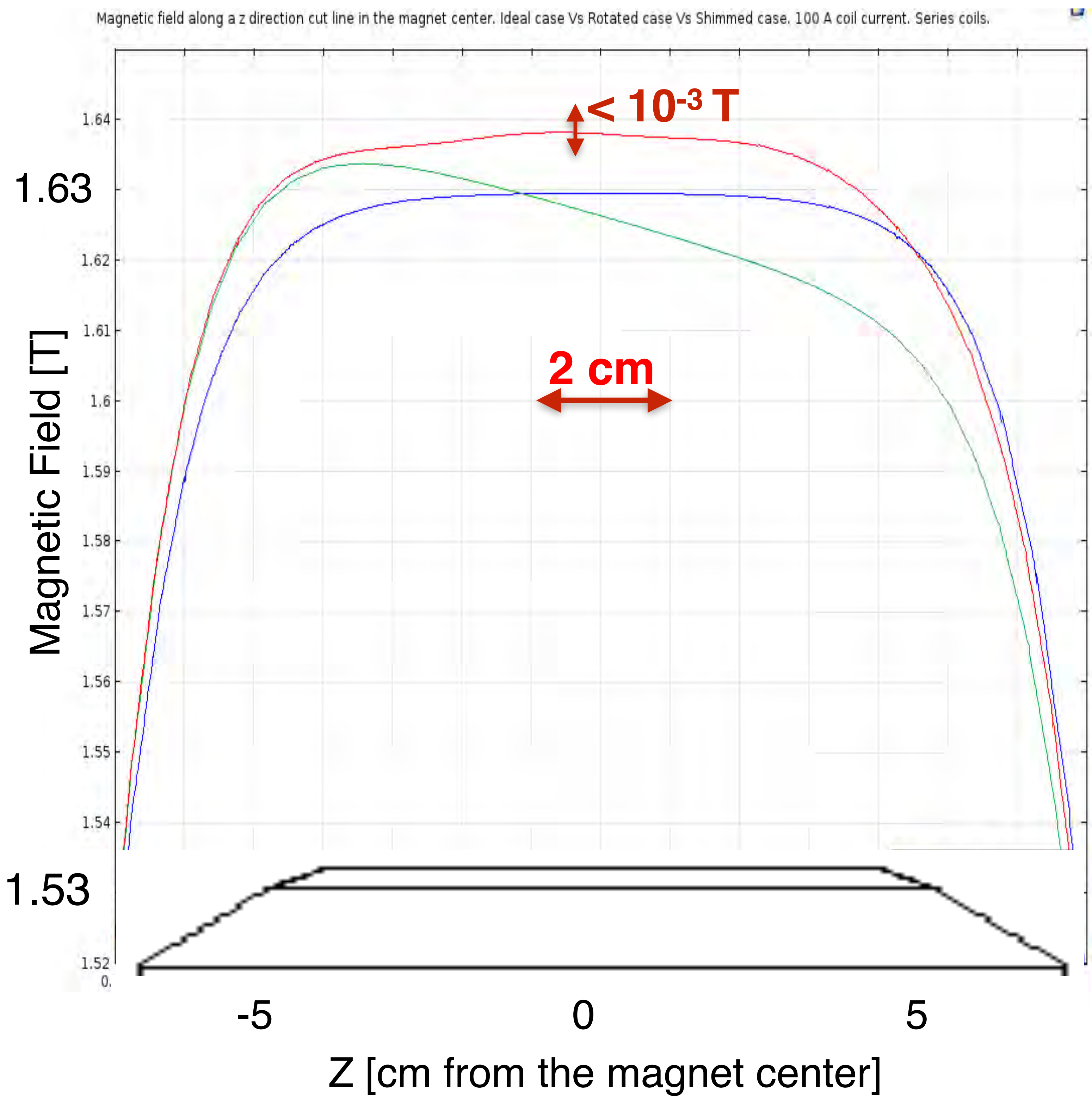


Fig.5. Pole skewness.

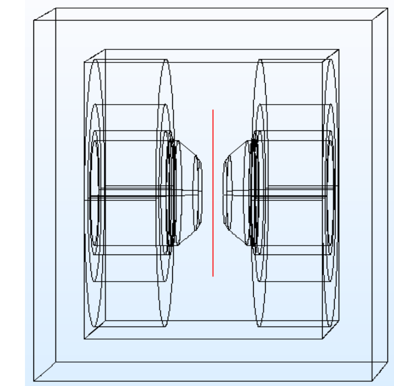
- Pole skewness decreases the field homogeneity to $6*10^{-3}$ T over 2 cm

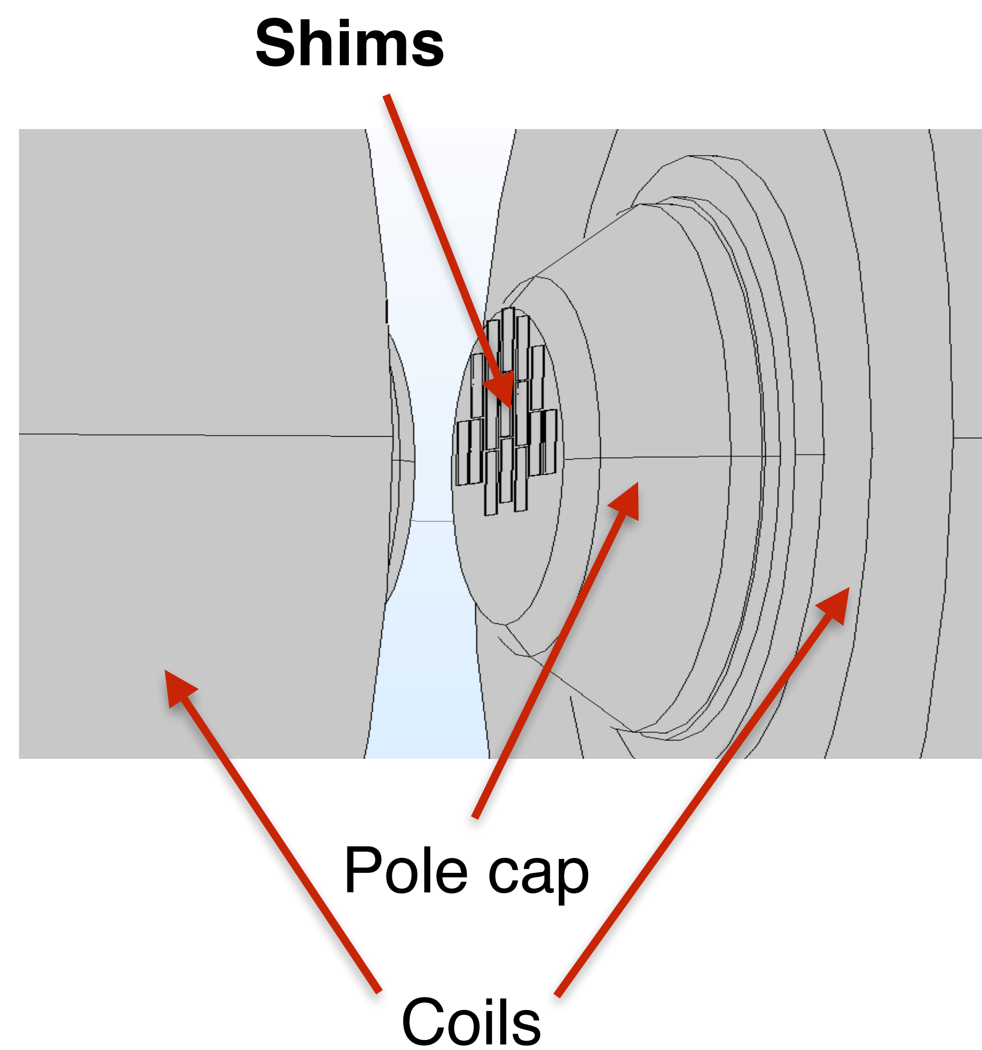
COMSOL Simulations – Shimming (trial and error procedure)



Field along Z line in the magnet center in the:

— ideal case
— poles skewed
— after shimming





COMSOL Simulations – Summary

Field homogeneity in the region of 2 cm in the magnet center:

- Ideal case: $< 10^{-4}$ T
- With poles skewed: $6*10^{-3}$ T
- With Shimming: $< 10^{-3}$ T

- The magnet can meet the requirement for the Hall Probe in the ideal case
- In non ideal conditions the homogeneity can be increased with shimming, decreasing the skew effect
- Simulations provide guidelines to how do the shimming

Field Mapping - Instrumentation Setup

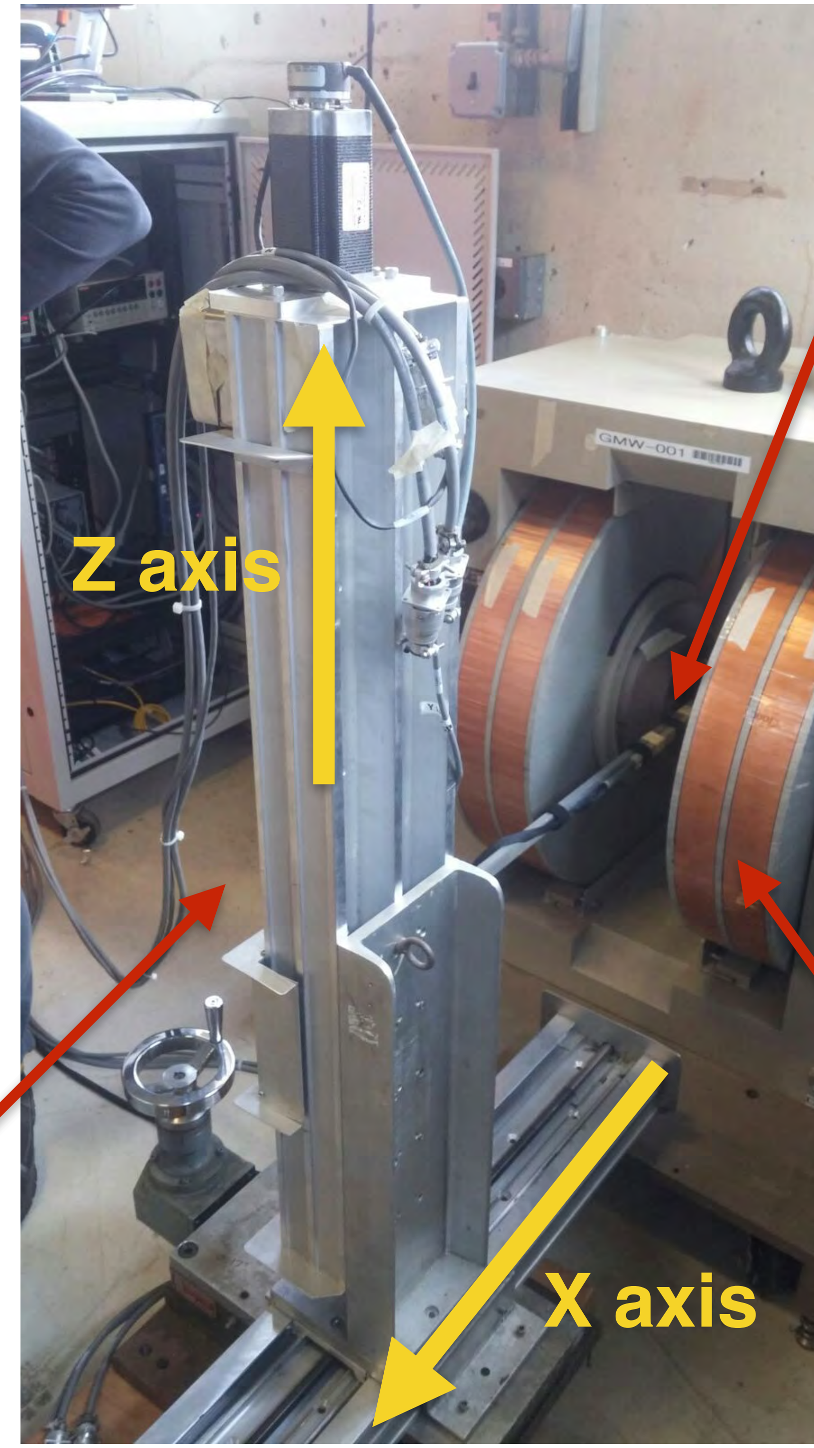
- **Magnetic Field mapping** using **NMR Probes** mounted on a **2 axis motion robot** with LabVIEW interface

For Metrolab PT 2025:

NMR Probe #4
range 0.7 - 2.1 T

NMR Probe #5
range 0.35 - 1.05 T

NMR Probe



Motion Robot

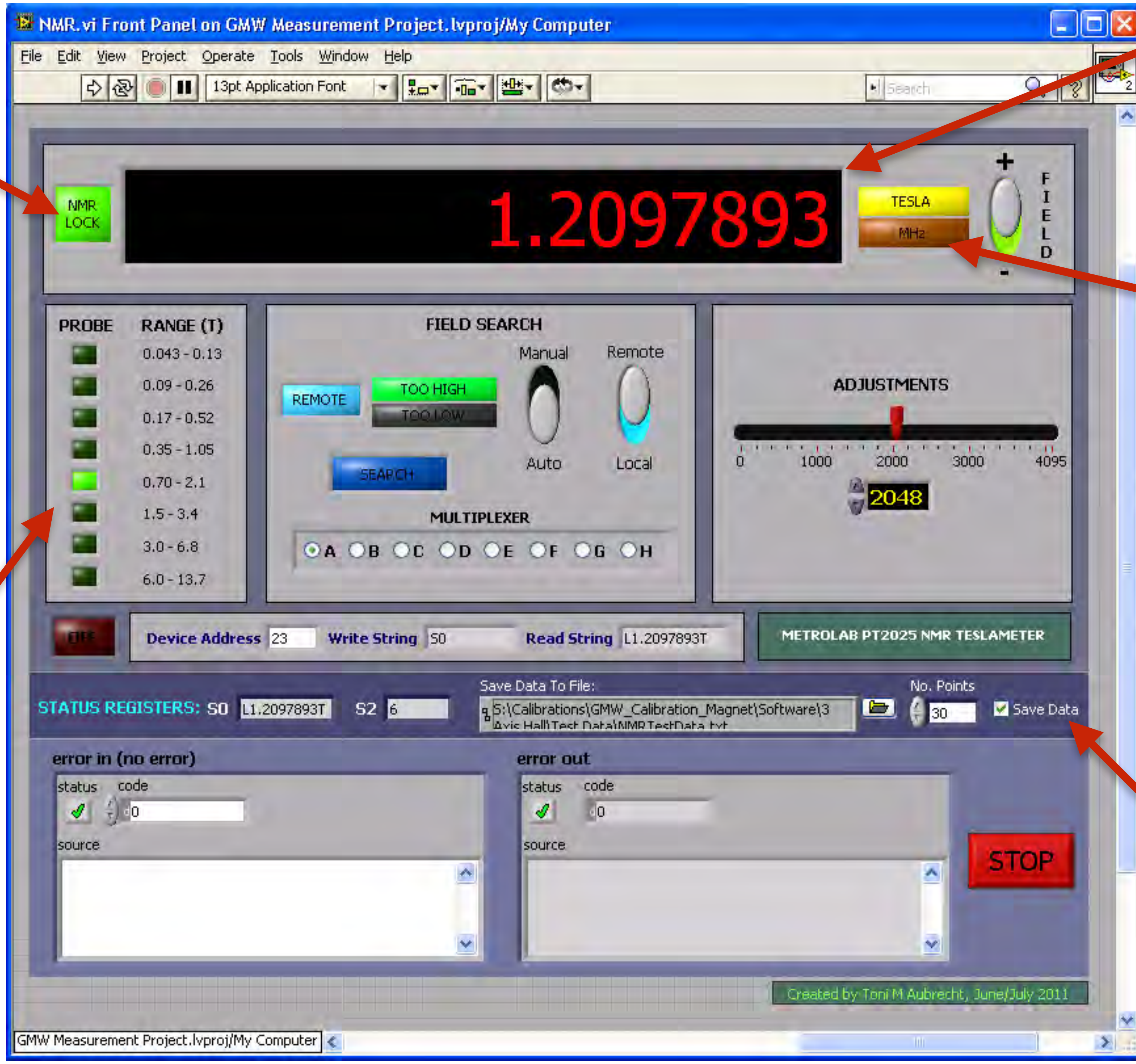
Electromagnet

Field Mapping - LabVIEW interface - NMR Probes reading

Light indicates if the NMR "has lock" the field

Magnetic field measured value

Switch to read the field or the resonant frequency of the NMR Probe active sample

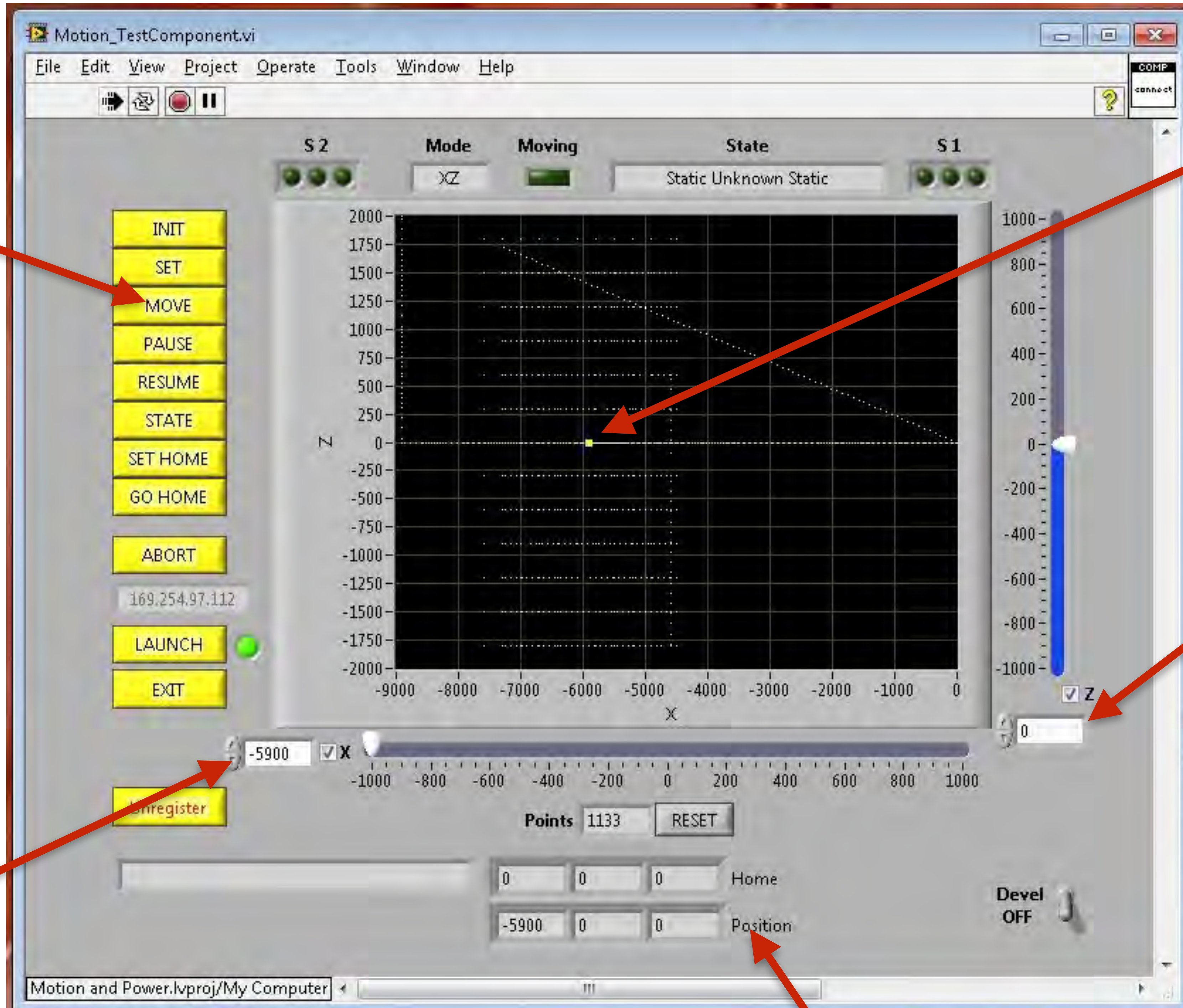


Lights indicate which probe is connected and its measurement range

Save the data in a spreadsheet file

Field Mapping - LabVIEW interface - Robot Movement

Button to move the robot



Actual robot position

Motor step along Z axis

Motor step along X axis

Robot position (x y z coordinates), relative to the home position

Field Mapping - Instrumentation Setup

Power Supply

- Manual supply current setting, using fixed steps

Water cooling control panel

DANFYSIK ULTRASTAB SATURN
Current Transducer

- feedback current measurement for power supply control

Field Mapping - Instrumentation Setup

Multimeters

- to measure a voltage proportional to the power supply current

- Keithley Model 2001 Multimeter
- Precision of 10^{-5} V

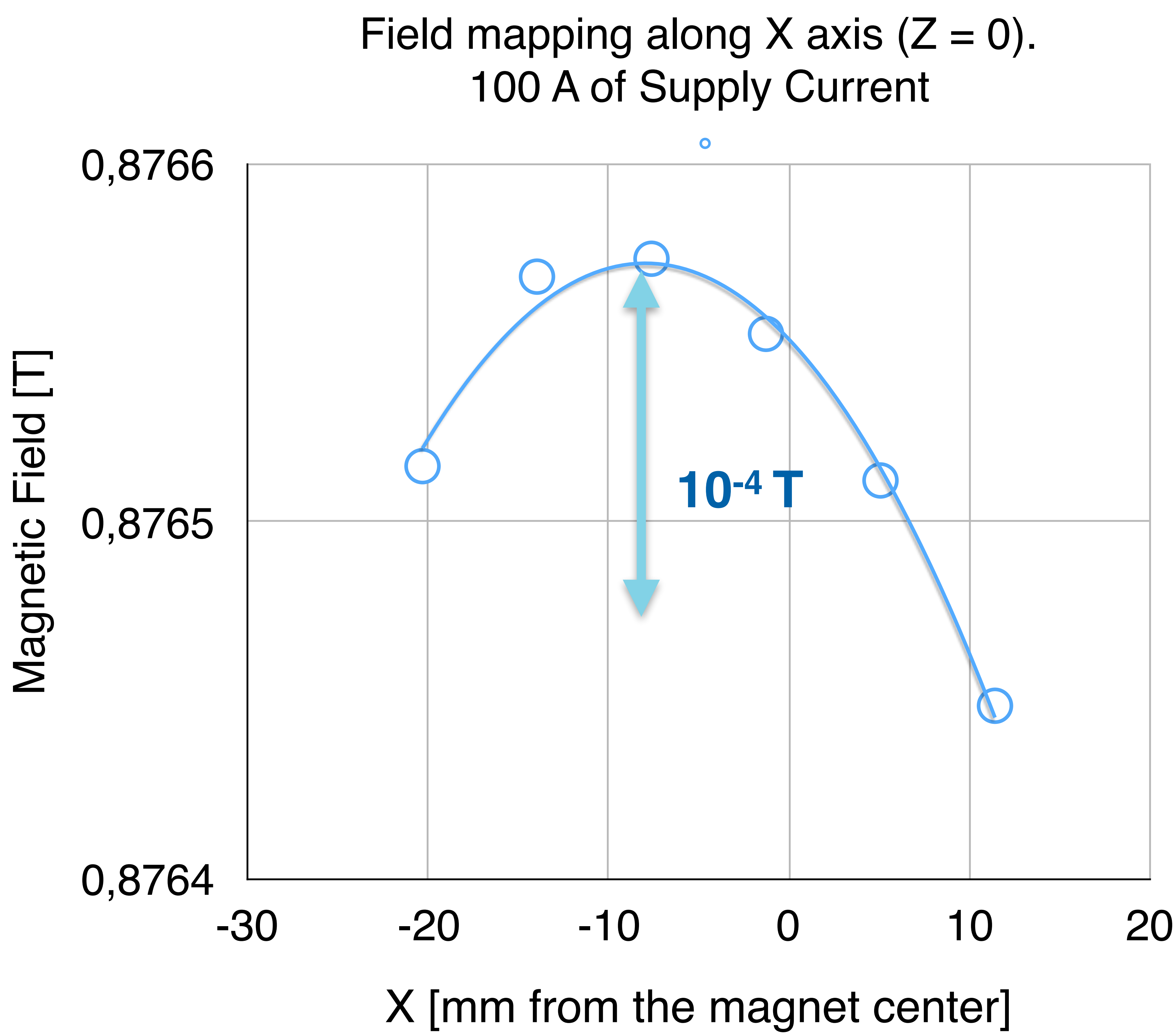
- Agilent 3458A Multimeter
- Precision of 10^{-6} V

- to measure the power supply voltage

- Hp 3457 A
- Precision of 10^{-4} V

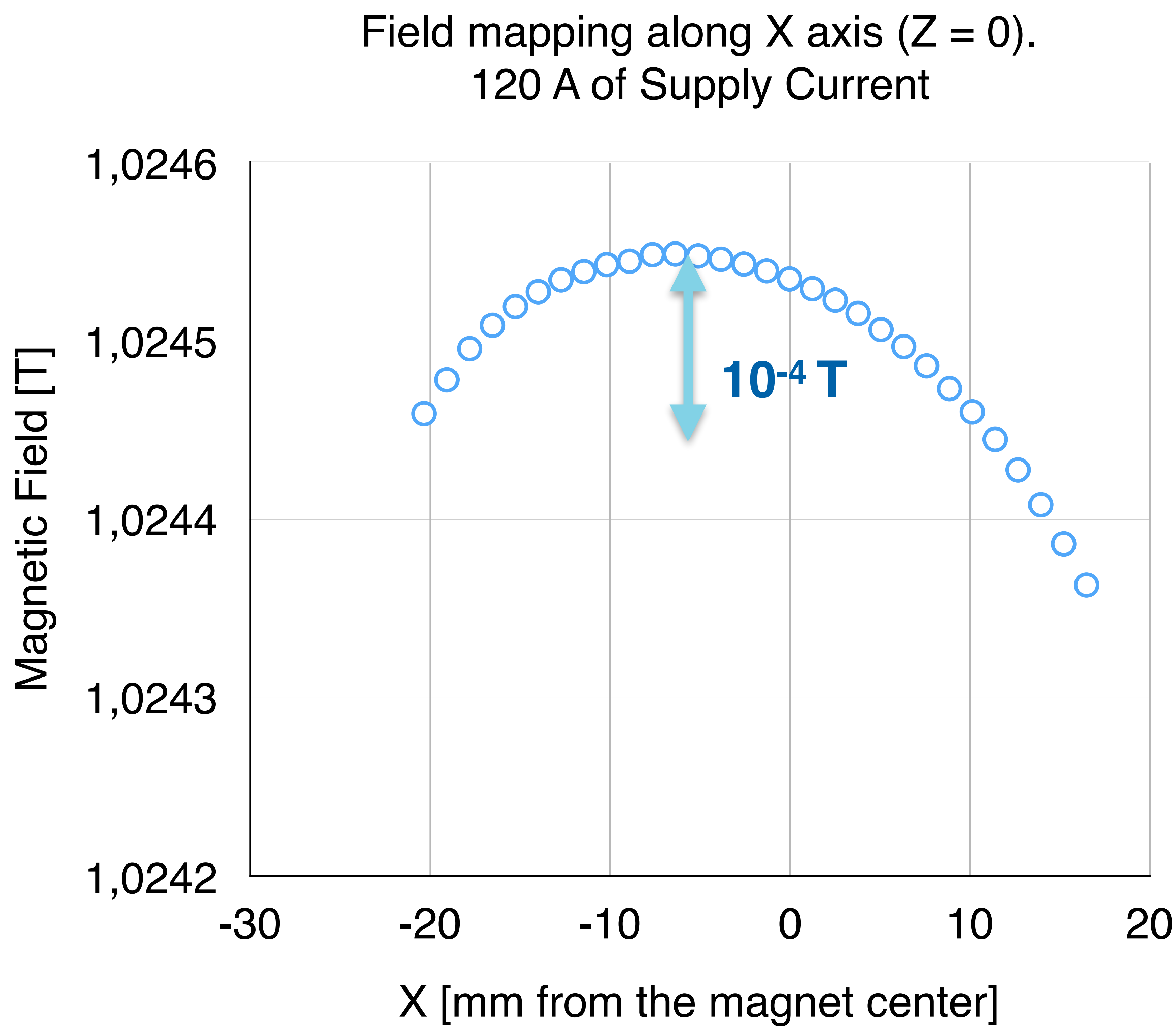
Field Mapping - Coarse 1D field Mapping

- Map resolution: 6.35 mm (step size 500 in X movement)
- The max field value is not in the magnet center
- Homogeneity of 10^{-4} T
- Only a small region can be measured: Probe #5 is insensitive if gradient is larger than 250ppm/cm)

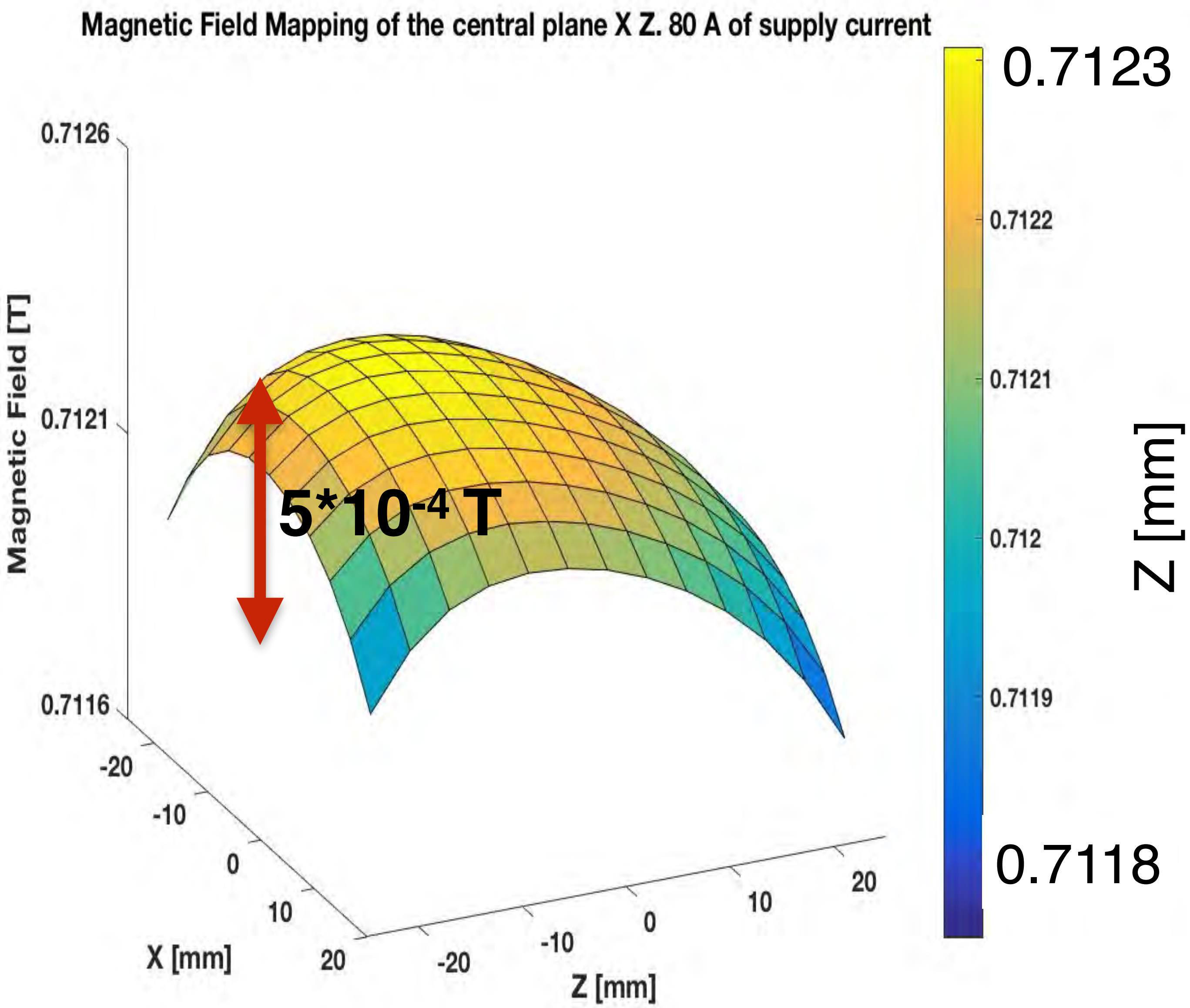


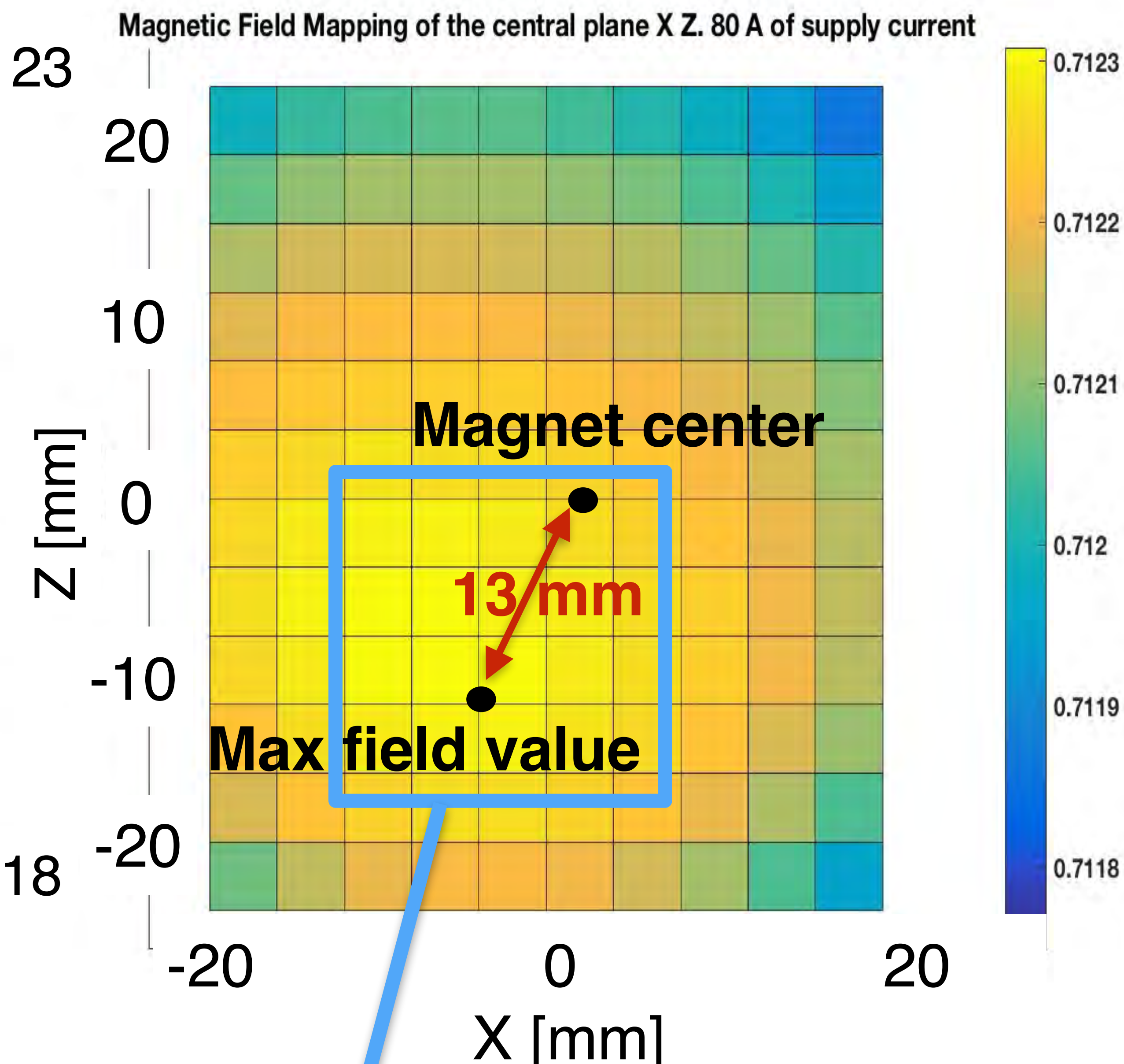
Field Mapping - Finer 1D field Mapping

- Map resolution: 1.27 mm (step size 100 in X movement)
- The max field value is not in the magnet center
- Homogeneity of 10^{-4} T
- Only a small region can be measured: Probe #5 is insensitive if gradient is larger than 250ppm/cm)



Field Mapping - 2D Field Mapping - 80 A



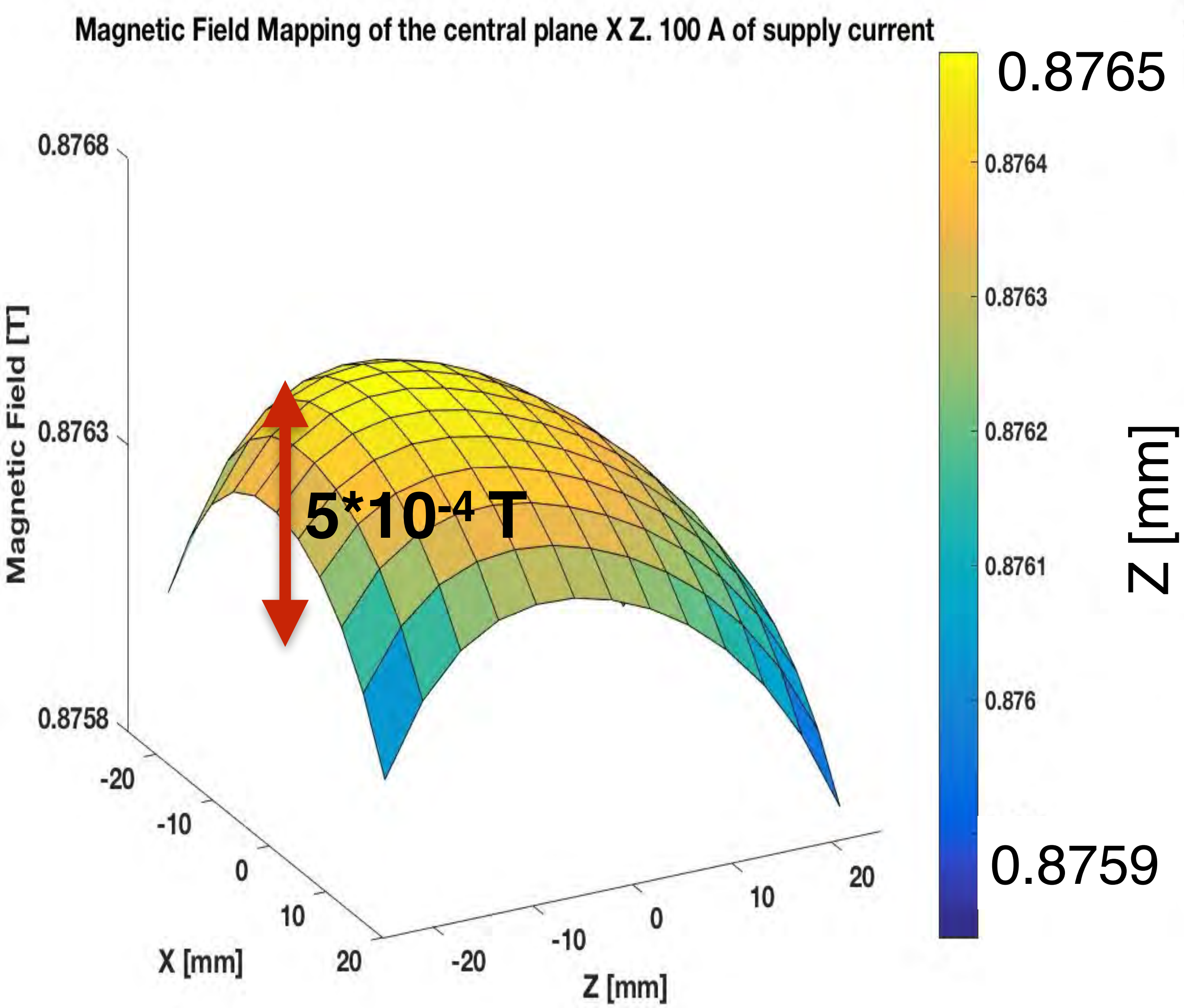


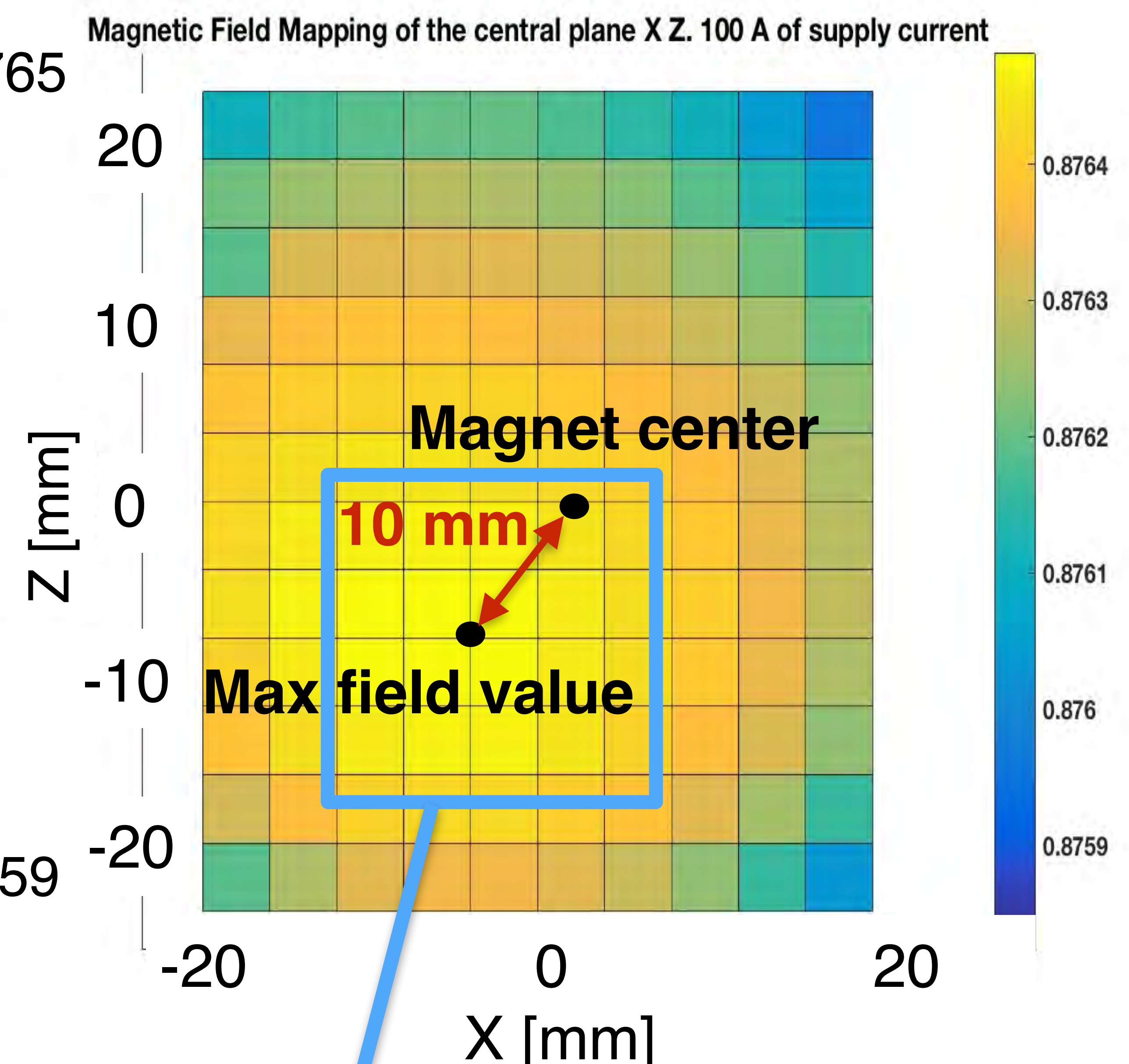
- Map resolution: 3.81 mm
- Supply current 80 A
- Field homogeneity

$5.6 * 10^{-4}$ T in the entire plane

$1.3 * 10^{-4}$ T in a 2 cm * 2 cm region

Field Mapping - 2D Field Mapping - 100 A





- Map resolution: 3.81 mm
- Supply current 100 A
- Field homogeneity

$6.7 * 10^{-4}$ T in the entire plane

$1.5 * 10^{-4}$ T in a 2 cm * 2 cm region

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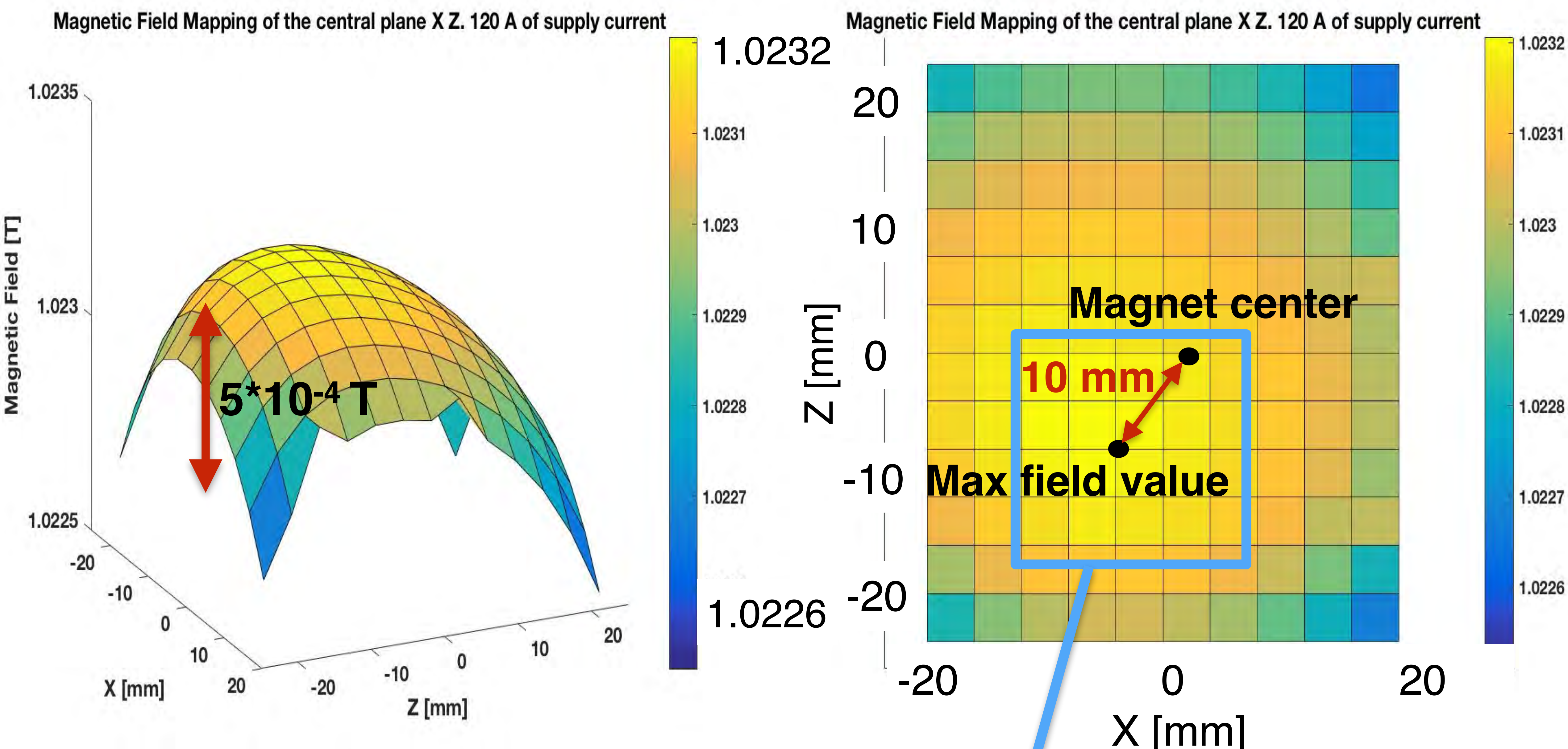
Field Mapping - 2D Field Mapping - 120 A



- Map resolution: 3.81 mm
- Supply current 120 A
- Field homogeneity

$7.0 * 10^{-4}$ T in the entire plane

$1.4 * 10^{-4}$ T in a 2 cm * 2 cm region

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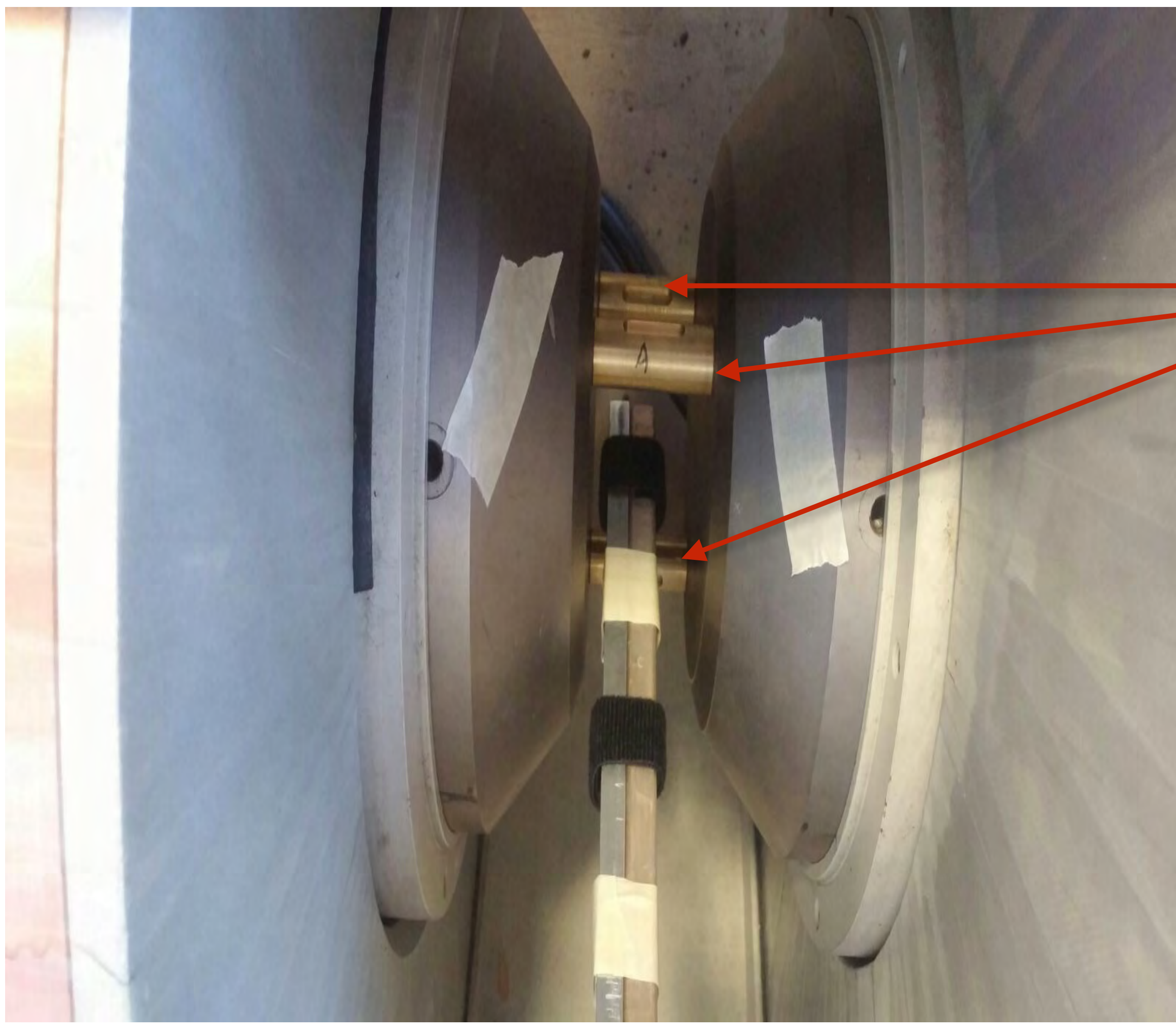
Field Mapping - 2D Field Mapping - Spacers

The maximum field value is not in the magnet center → The cause is pole skewness (measured about 1 mm → Use **pole spacers** to align the poles and reduce the skewness

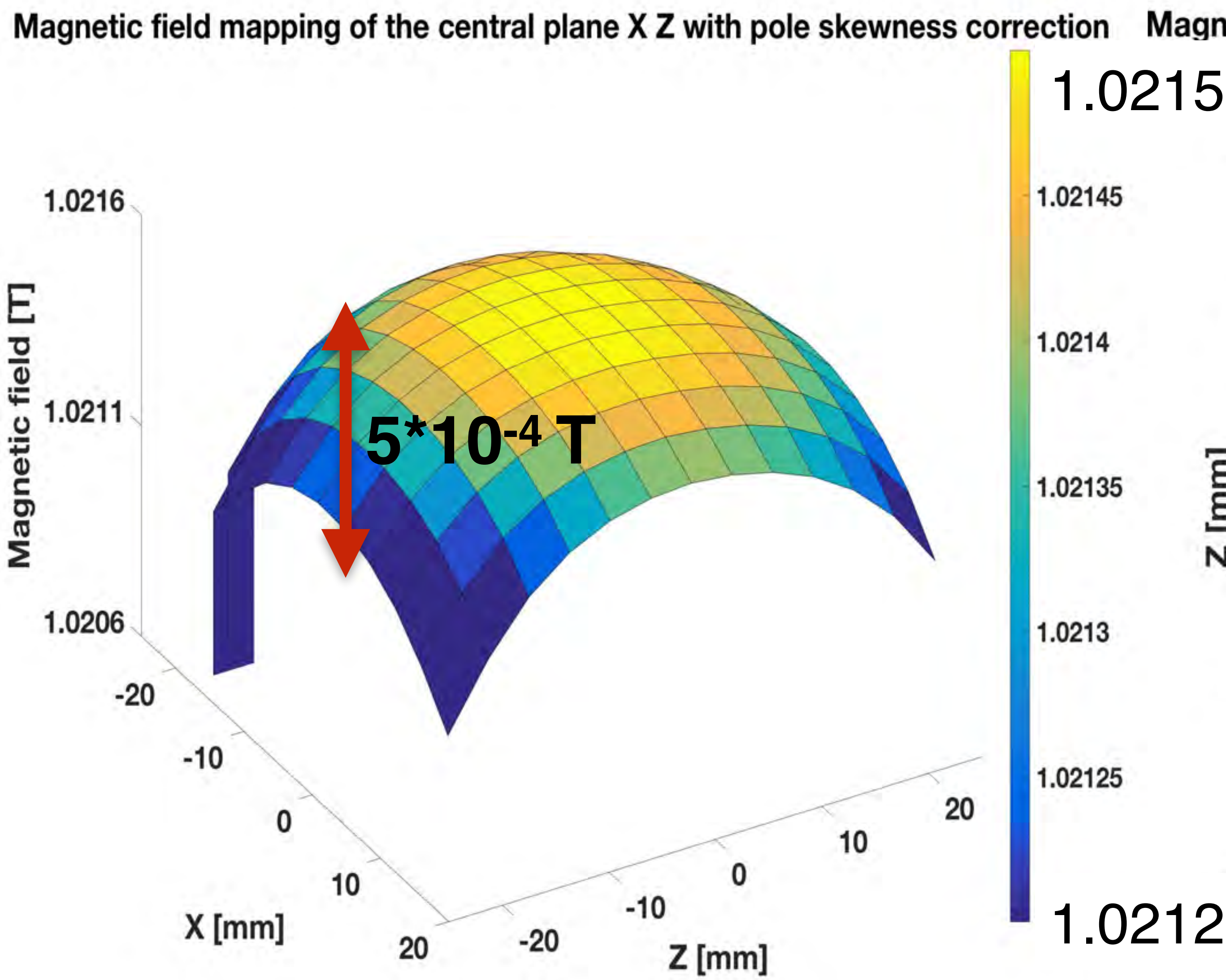


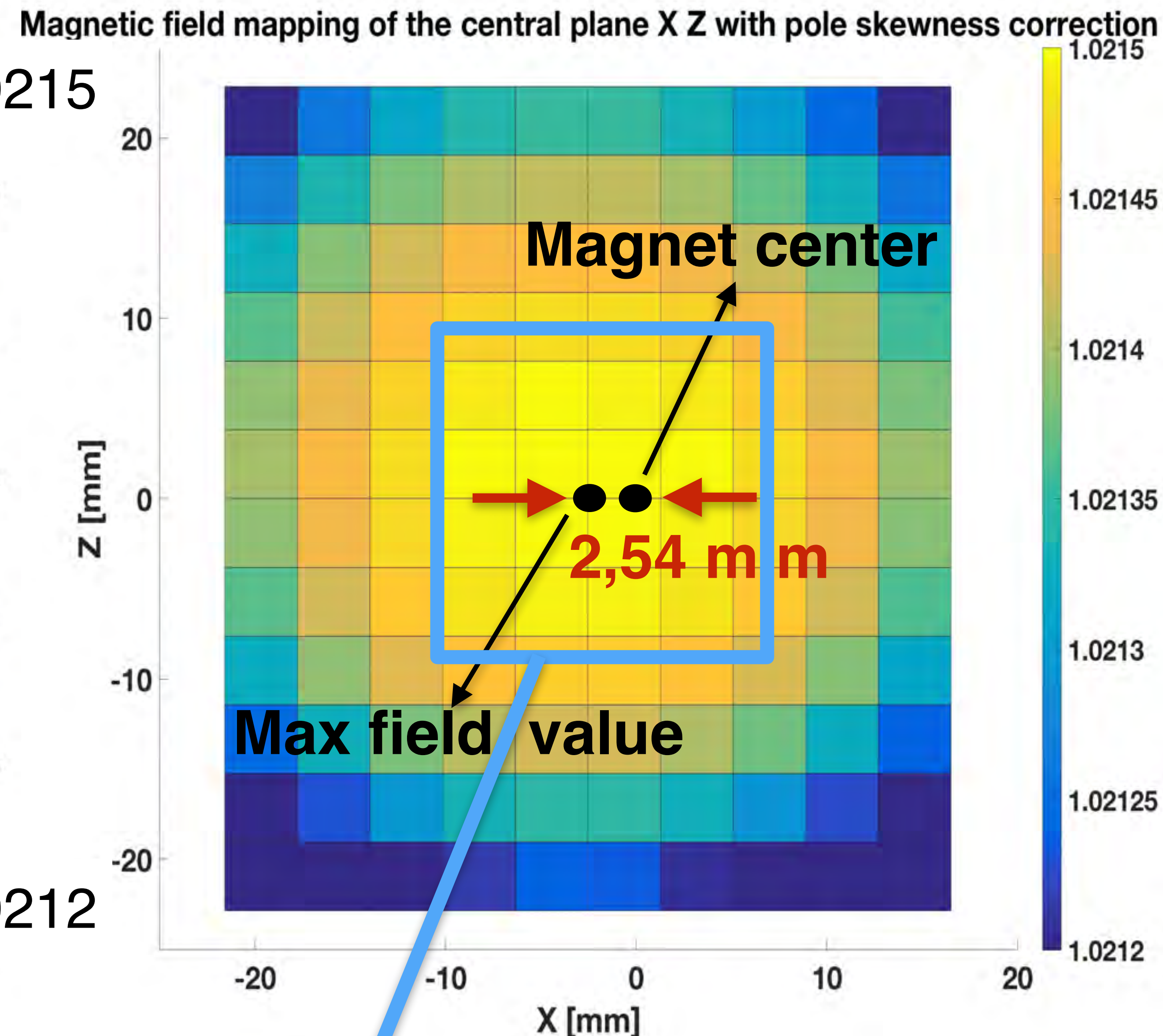
Pole spacers

Results

- The field is more **symmetric**
- **homogeneity increased** from $1.4 \cdot 10^{-4}$ T to $8.8 \cdot 10^{-5}$ T in the region of 2*2 cm…

Field Mapping - 2D Field Mapping - Spacers





- Map resolution: 3.81 mm
- Supply current 120 A
- Field homogeneity

$6 * 10^{-4}$ T in the entire plane

$8.8 * 10^{-5}$ T in a 2 cm * 2 cm region

Error on center position of the robot about 3 mm

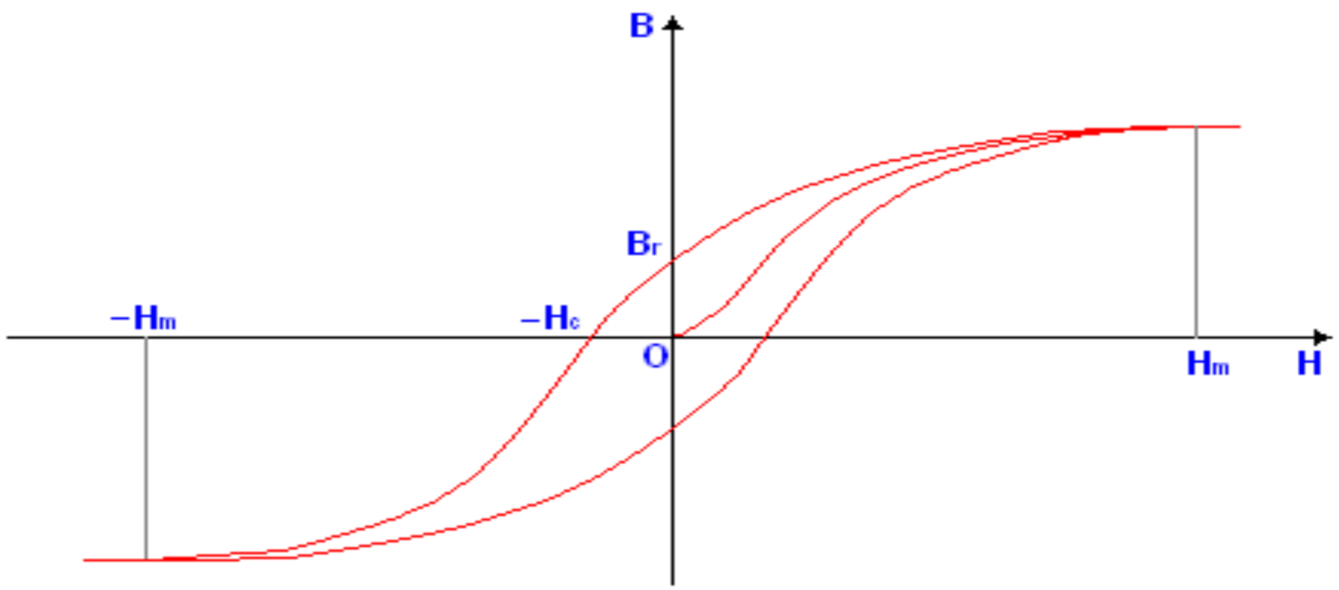
Field Mapping - Magnetic Hysteresis

Hysteresis

- System's dependence on the present and past input
- The history of the state assumed by the system affects the behavior of present state

Explanation:

- When an external magnetic field is applied to a ferromagnetic material, the atomic dipoles align themselves with it
- When the field is removed, part of the alignment will be retained and the material hold a magnetization



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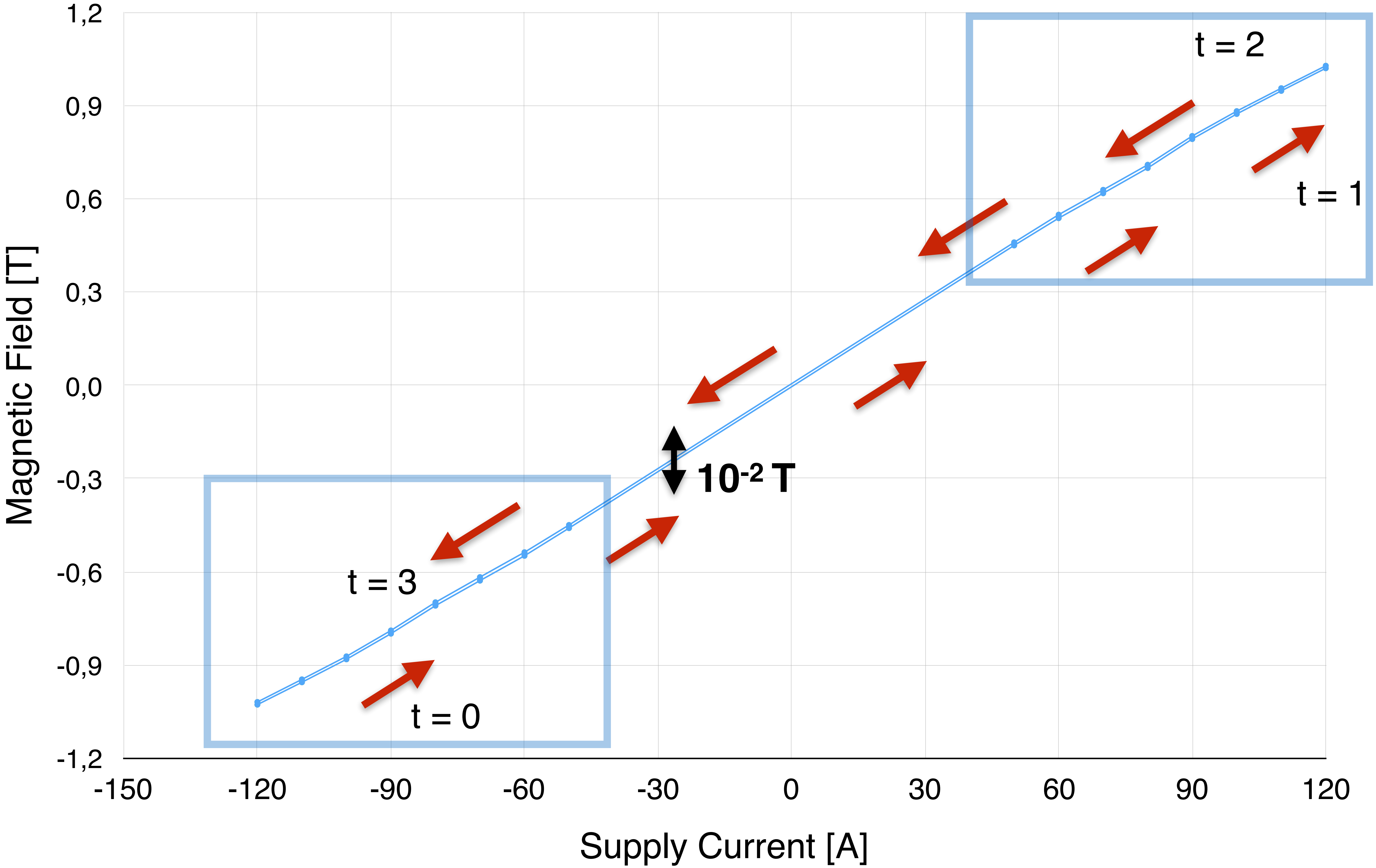
Field Mapping - Magnetic Hysteresis



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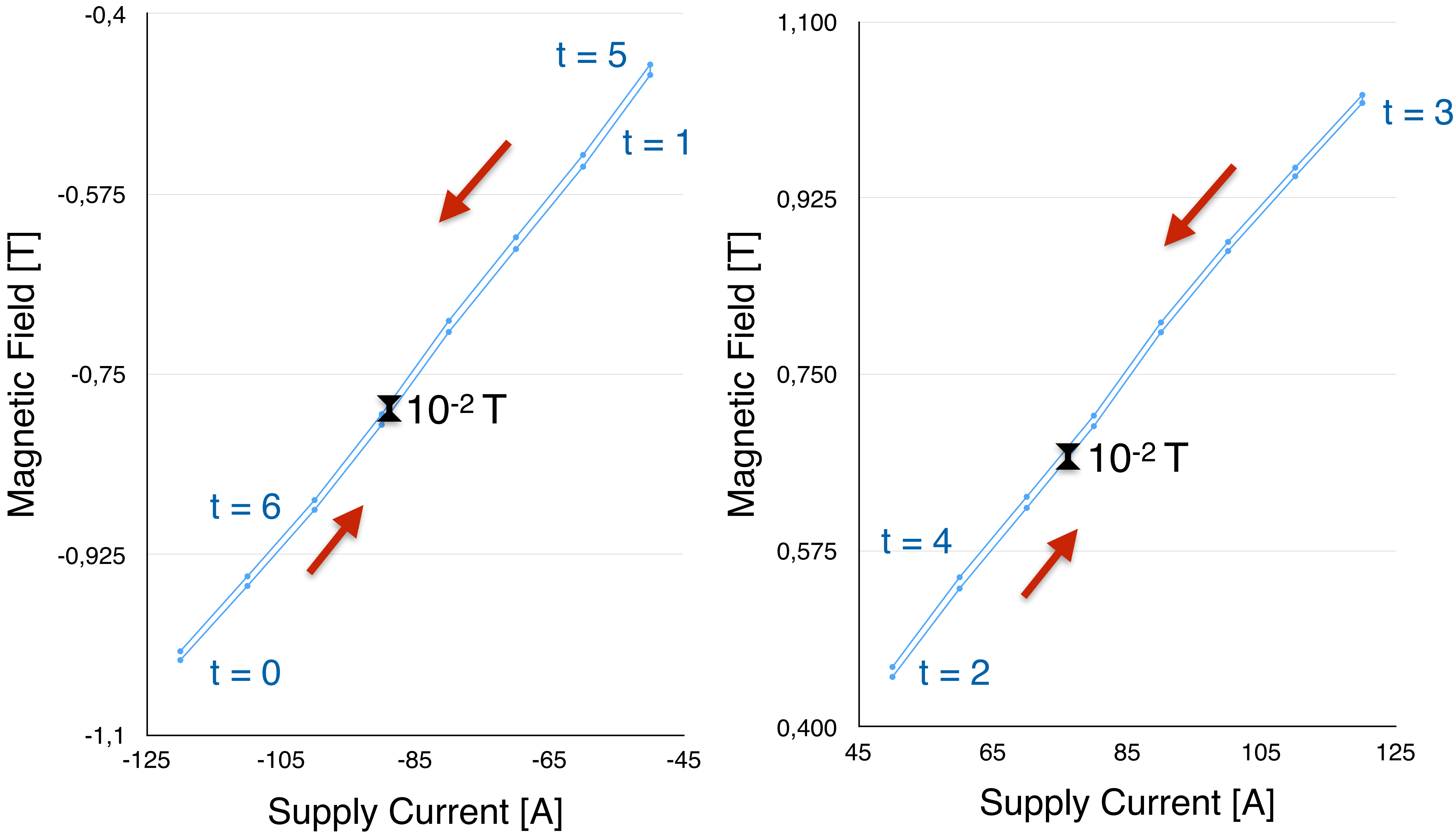
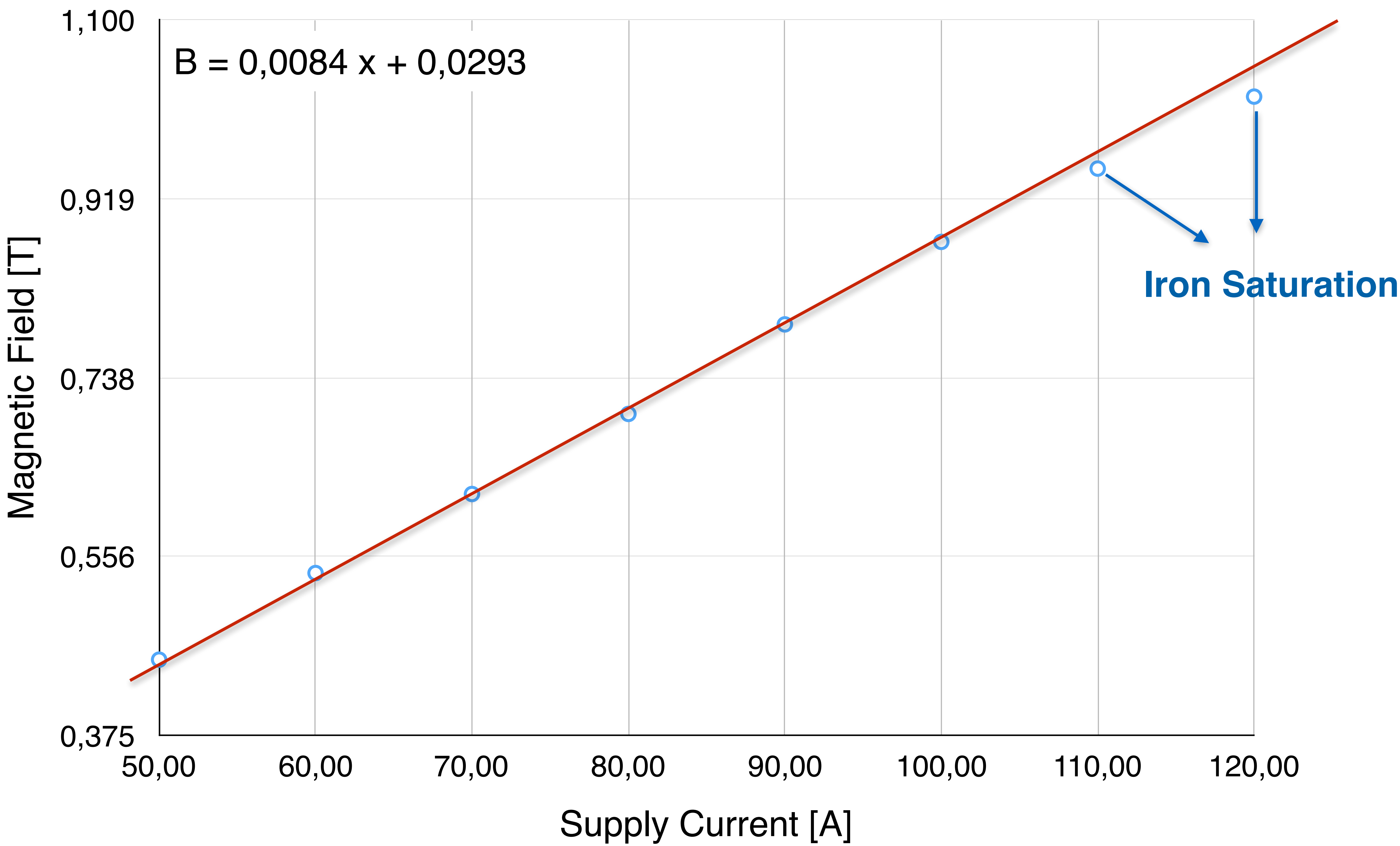
Field Mapping - Magnetic Hysteresis



Field Mapping - Field Vs Current plot



Field Stability over time - 85 F

Several measurements of the field with 80 A of supply current → Stability of 10^{-3} T

Degausssing

↓

0 A

↓

80 A

↓

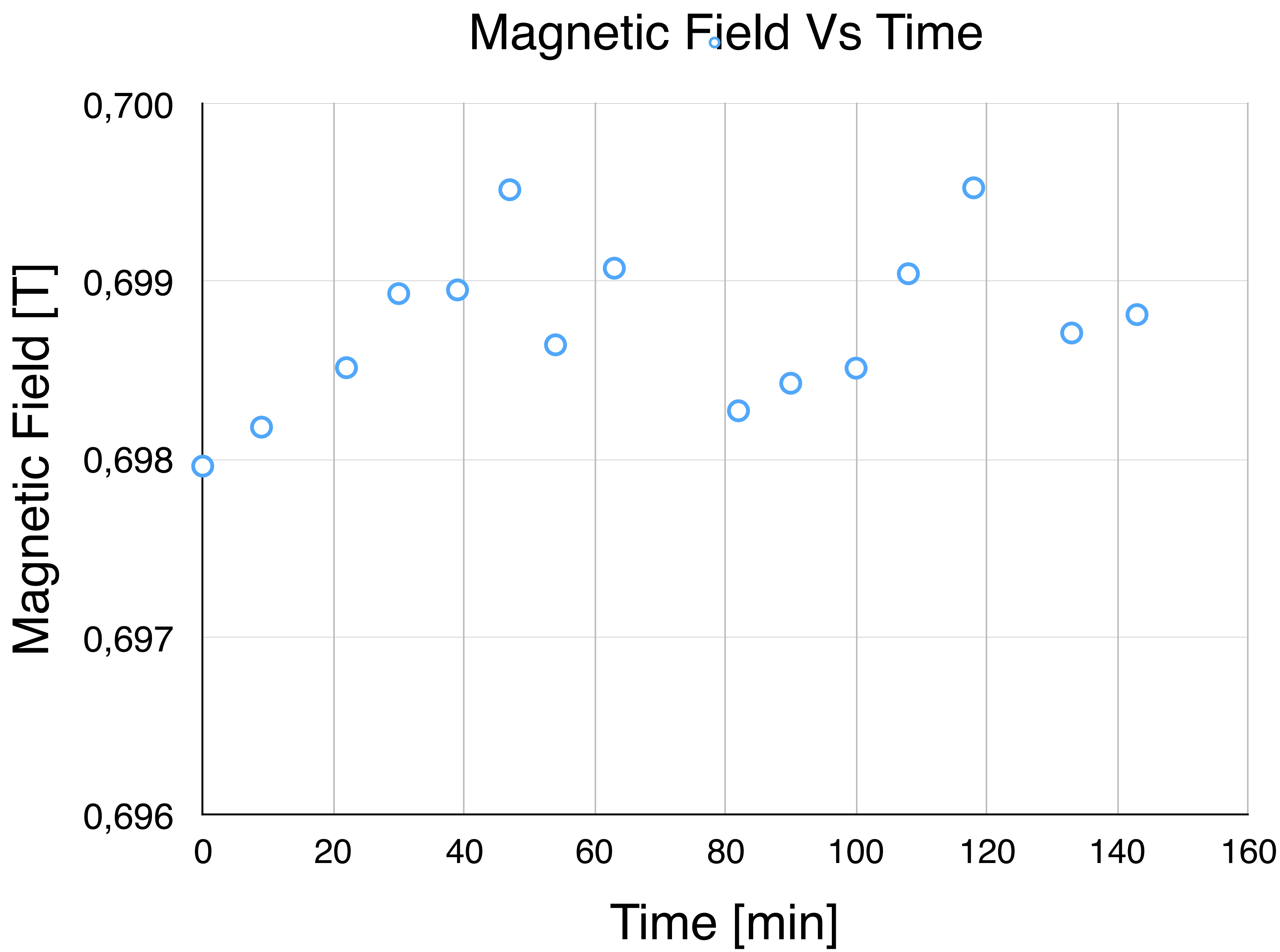
Degaussing

↓

0 A

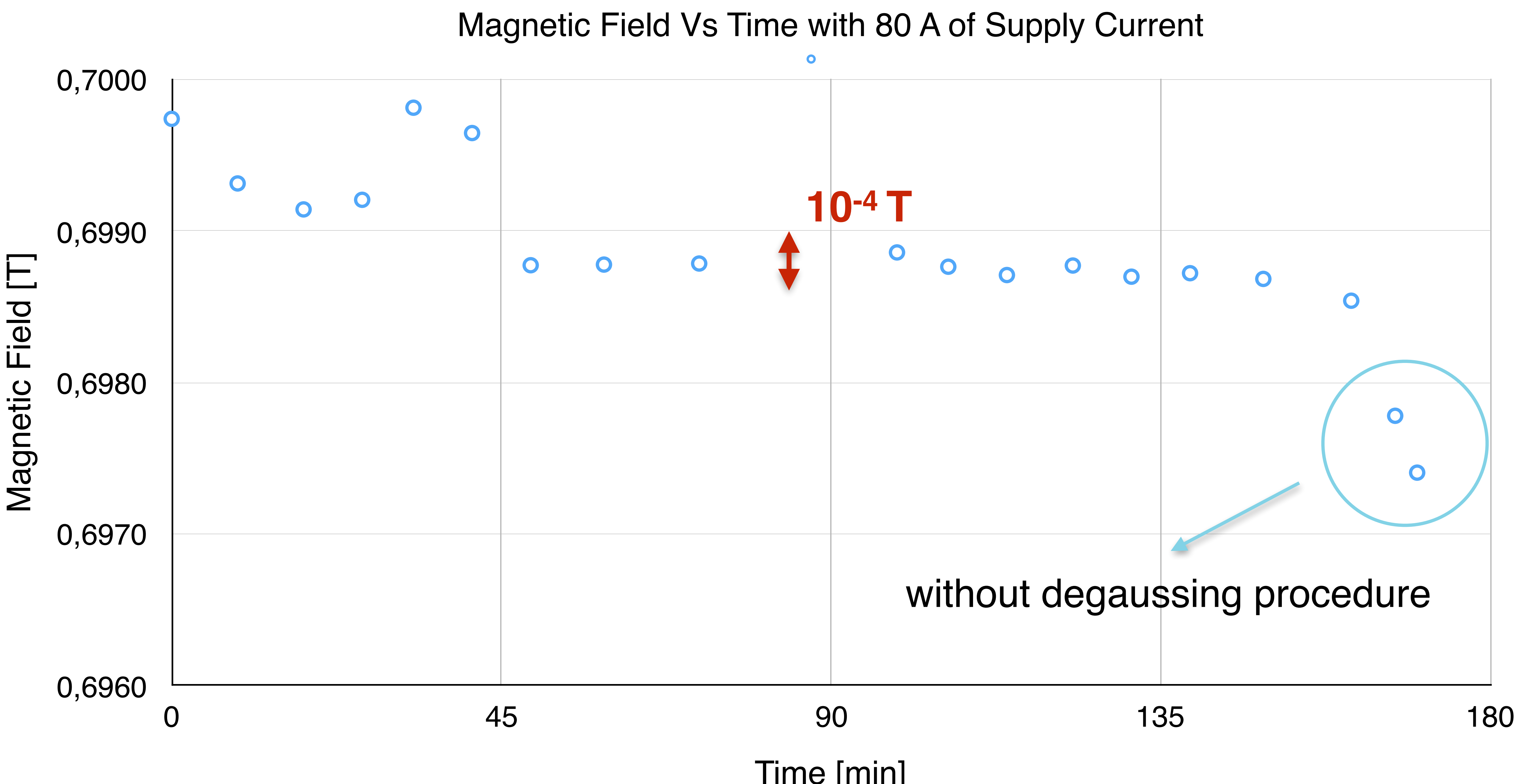
↓

80



Field Stability over time - 100 F

- Increasing the temperature set point, the magnet goes in a more stable temperature condition
- Field stability goes up to 10^{-4} T



Field Mapping - Magnetic Hysteresis

- Hysteresis can explain the field difference of 10^{-3} T observed in two different days mapping

- However, there is still a variance in the field, which can be attributed to a variation in the power supply; increasing the set-point temperature helps to stabilize the power supply

- Lessons learned:
  - apply a degaussing procedure to loose previous memory of the magnet
  - Ramp to the desired current plateau slowly
  - Stabilize the power supply internal temperature

  - We obtained a stability of 10^{-4} in the final measurements

Results

- We can not go over 10^{-4} T of field stability because the power supply stability is limiting the mapping
- With pole spacers the field homogeneity is increased from $1.4*10^{-4}$ T to $8.8*10^{-5}$ T in a 2 cm * 2 cm region
- Shimming procedure can potentially increase the field homogeneity. Not done due to instability in power supply.
- Before the shimming procedure, one needs to work on stabilizing the power supply, not only do we need homogeneity over the mapped volume, but also over the time of the hall probe calibration to ensure repeatability of the measurement
- We are confident that one can achieve the value that meet the requirement for Hall Probe Calibration

Skills learned

Safety

- Electrical safety
- Radiological safety

Software

- Improvement of COMSOL (new electro static and temperature dependance)
- Basics of LabVIEW (write small program to read measurement values)

Magnetic field

- Magnetic field measurements: how do NMR Probes and Hall Probes work, differences, and applications
- How do a magnetic field test using advanced instruments
- Analyze the acquired data, understand some data inconsistency and show the results

- Interact with engineers, scientists and technicians at a national laboratory

Thank you for attention

APPENDIX 1 - Principle of operation of the NMR Probes

by Wikipedia & NMR Probe Manual

- All nucleons, have the intrinsic quantum property of **spin**, determined by the *spin quantum number* **S**.

- **Angular momentum** associated with the spin has a quantized magnitude and orientation. The angular momentum component along a z axis is:

$$P_z = m\hbar$$

  where ħ is the reduced Planck constant and **m** is the *magnetic quantum number*, that can take the values from -S to S in integer steps.

- We consider atoms with **S = 1/2** because NMR Probes use the property of Hydrogen atoms whose have S = 1/2.

- A charge particle with spin property has a **magnetic moment**.

APPENDIX 1 - Principle of operation of the NMR Probes

by Wikipedia & NMR Probe Manual

- The relation between the magnetic moment and the angular momentum is described by ***γ***, the **gyromagnetic ratio**.

$$\mu_z = \gamma S_z = \gamma m\hbar.$$

- In an atom with S = 1/2, m can take only 2 values (-1/2, 1/2): the atom have only two energy state, one with **parallel** magnetic momentum and the other **antiparallel**.

- Energy of a magnetic momentum in the presence of an external magnetic field:

$$E = -\boldsymbol{\mu} \cdot \mathbf{B}_0 = -\mu_{\mathrm{z}} B_0 = -\gamma m\hbar B_0$$

$$\Delta E = \gamma\hbar B_0$$

- Parallel state is more stable than antiparallel state: a bigger number of atoms have a magnetic moment parallel with the external field and a smaller number are antiparallel

APPENDIX 1 - Principle of operation of the NMR Probes

by Wikipedia & NMR Probe Manual

- When an external electromagnetic radiation of a frequency of

$$\nu_0 = \frac{\Delta E}{h} = \frac{\gamma B_0}{2\pi} \qquad \text{(Larmor Frequency)}$$

  the atoms absorb energy and from the lower energy state they go in the higher energy state. Larmor frequency depends both on the external magnetic field and the material and is in the range of radio frequency

How do NMR Probes work

- An active sample rich of hydrogen atoms is wound by radio frequency coils.
- If the sample is inside an external magnetic field and the coils generate an electromagnetic field at the sample Larmor Frequency, the atoms of the sample absorb energy, decreasing the quality factors of the coils.
- Measuring the attenuation of the radio frequency voltage amplitude across the coils, and amplifying this signal, the NMR Probe Electronic can detect the NMR signal.

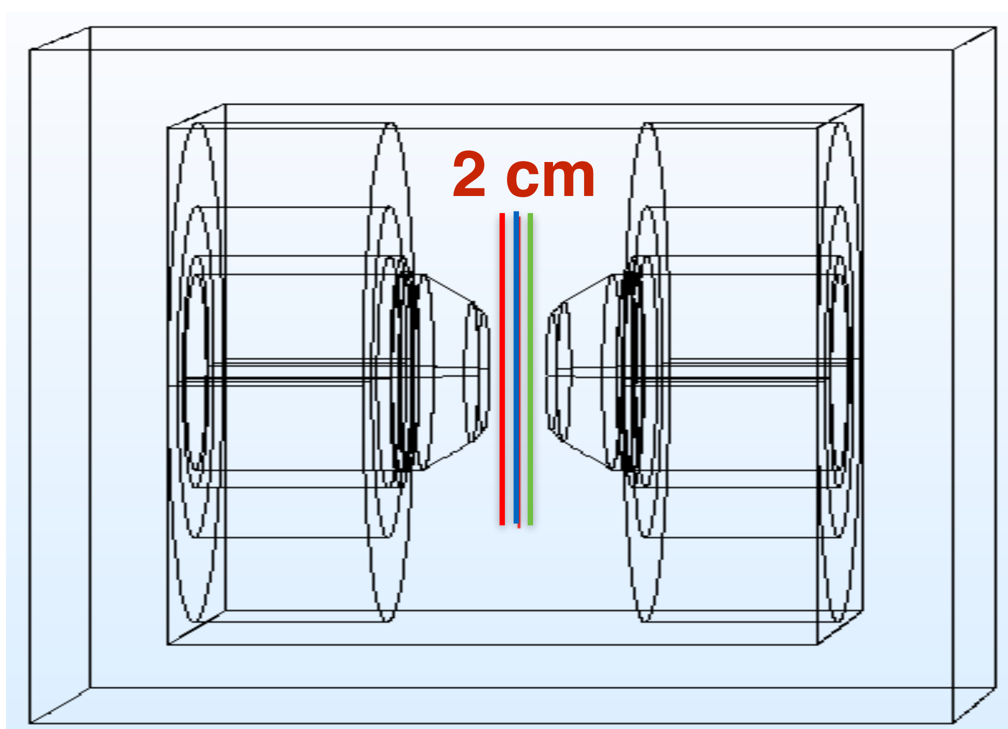
APPENDIX 1 - Principle of operation of the NMR Probes

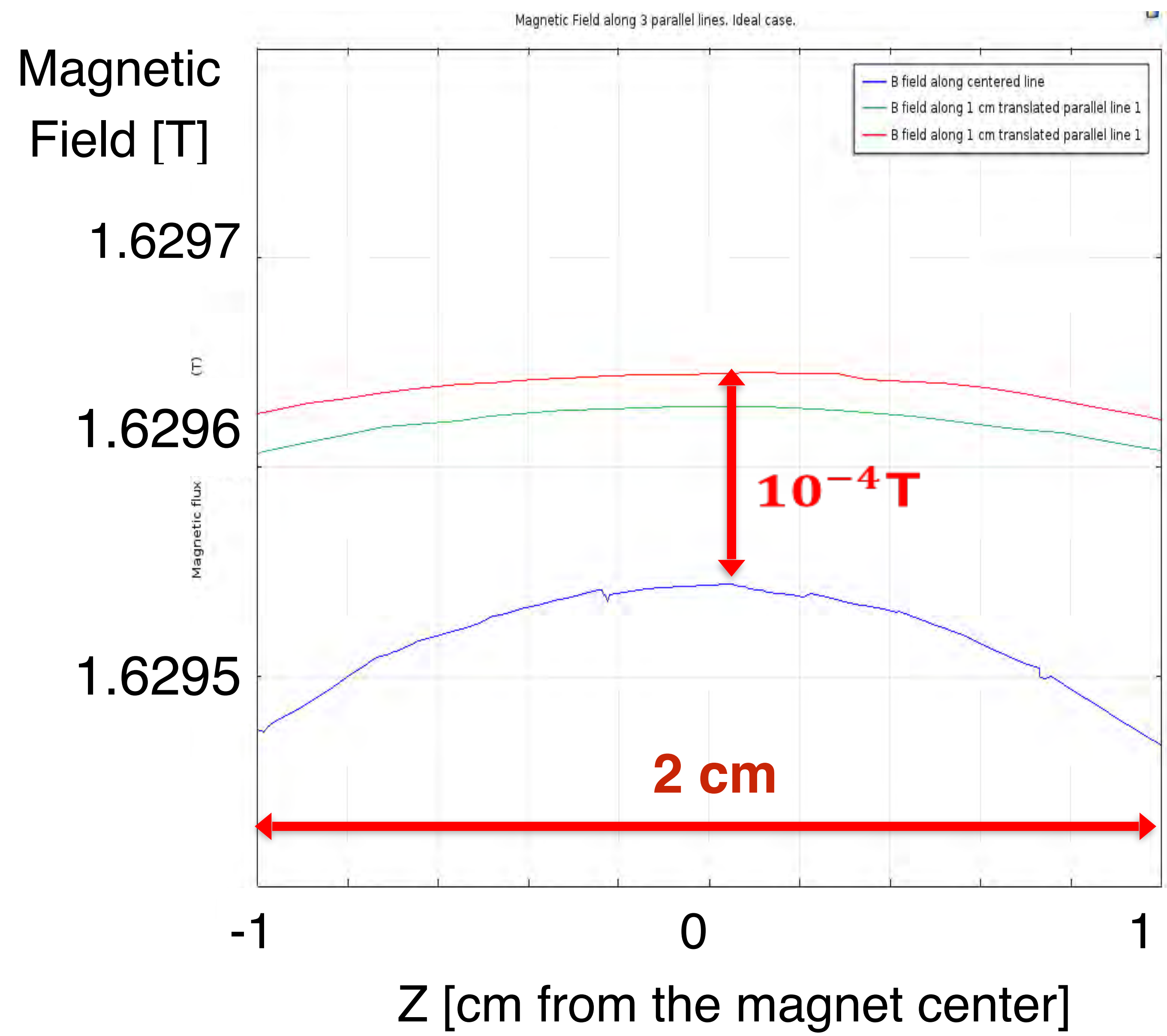
by Wikipedia & NMR Probe Manual

- Knowing the frequency at which the sample absorb energy, the external magnetic field can be calculate because there is a linear correlation between frequency and field.

APPENDIX 2 - COMSOL Simulations - Ideal case

Magnetic Field along 3 parallel line in the magnet center

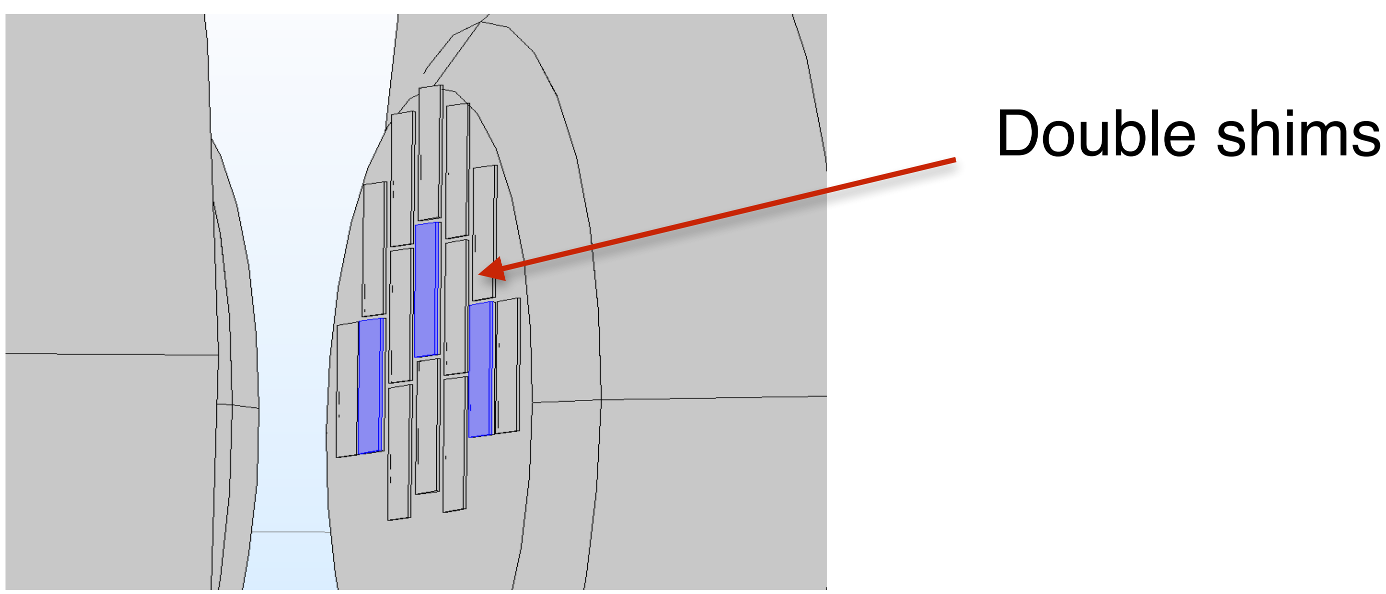


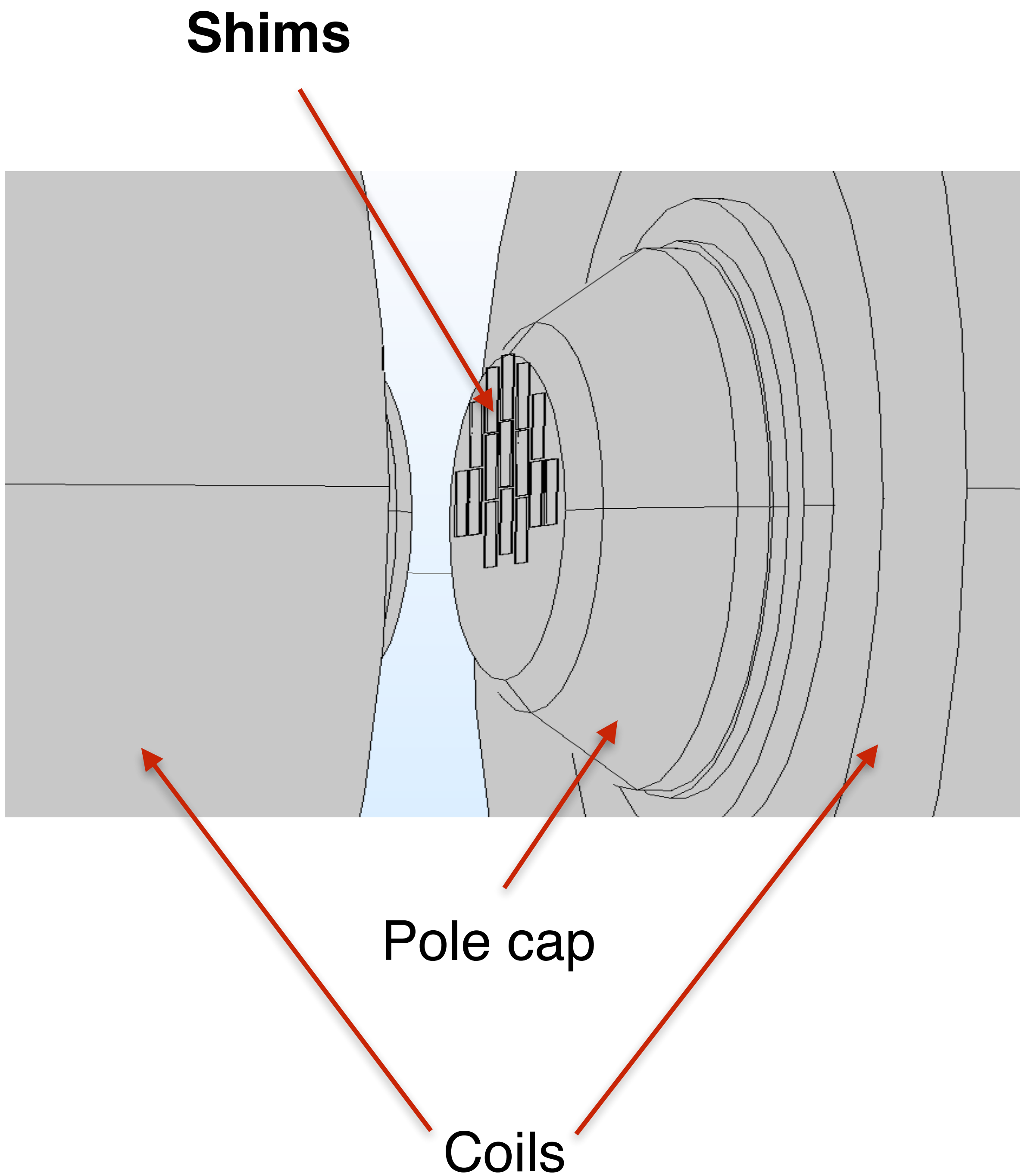


APPENDIX 2 - COMSOL Simulations – Shimming

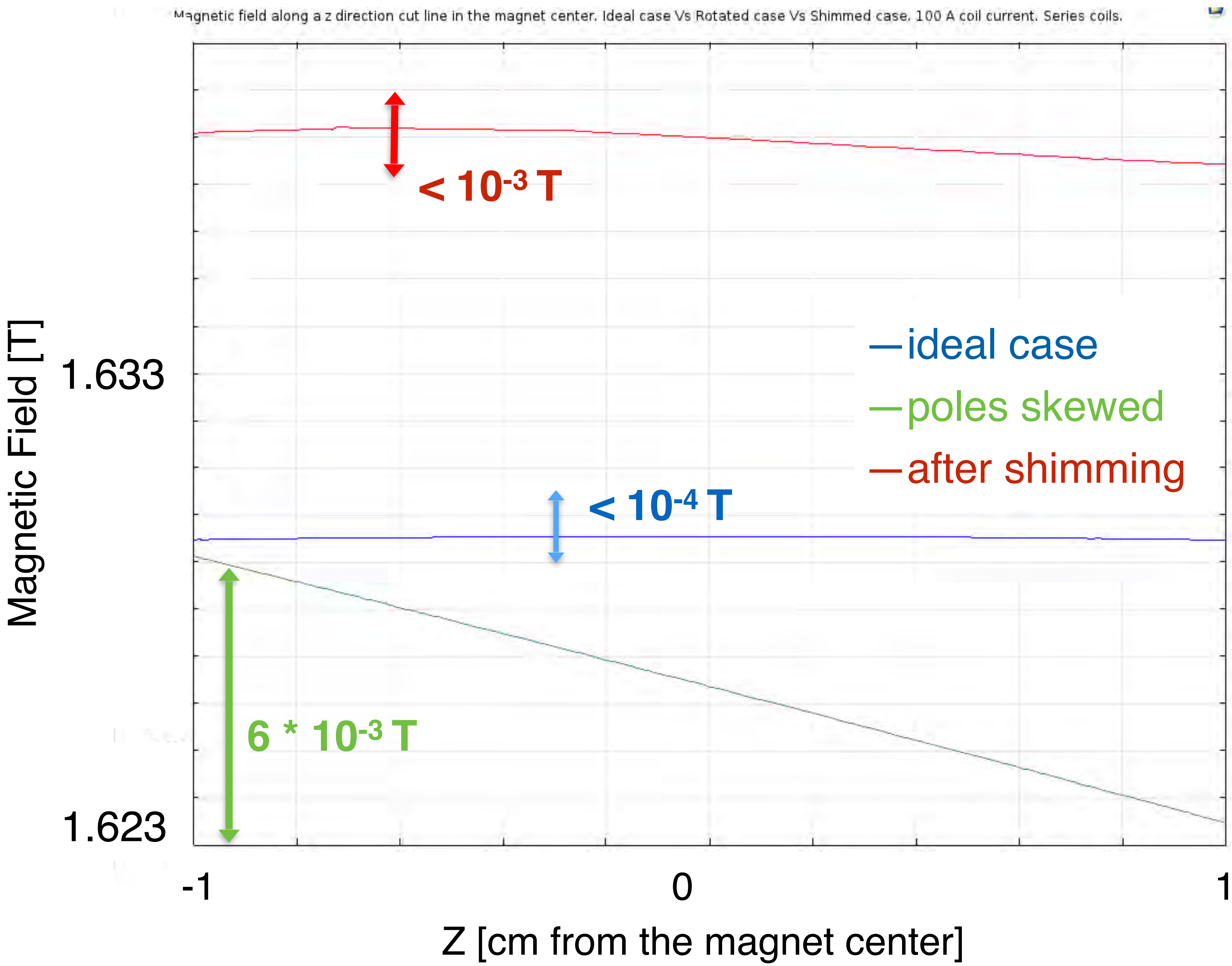
Shims used in the model:

- thin iron strips of **430 μm * 3 cm * 1cm**
- added on the pole surface where poles are less closer due to skewness
- compensate the field in the region where it is smaller
- **Trial and error** procedure





APPENDIX 2 - COMSOL Simulations – Shimming



Field along Z line. Zoom in the region of 2 cm in the magnet center.

Result:

- Shims increase the field homogeneity and compensate the pole skewness